1969

Development of a method for measuring and describing soil surface roughness

Howard David Currence
Iowa State University

CURRENCE, Howard David, 1940-
DEVELOPMENT OF A METHOD FOR
MEASURING AND DESCRIBING SOIL
SURFACE ROUGHNESS.

Iowa State University, Ph.D., 1969
Engineering, agricultural

DEVELOPMENT OF A METHOD FOR MEASURING

AND DESCRIBING SOIL SURFACE ROUGHNESS

by

Howard David Currence

A Dissertation Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major Subject: Agricultural Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State University
Ames, Iowa

1969

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

INTRODUCTION

Billions of dollars are spent annually in tilling agricultural land for crop production. The factors that necessitate this expenditure vary with the cropping practices and soil conditions in a given area. Reduction of bulk density, weed control, seedbed preparation, crop residue management, fertilizer placement, soil aeration, wind and water erosion control, and changes in cropping systems are the major reasons for tillage. Although soil has been tilled for many years, the evaluation of a given tillage operation is still very difficult. The objectives of tillage are known only in vague terms because fast, reliable methods have not been developed to measure the many effects of tillage. Depending upon the soil and weather conditions before and after tillage, a given tillage operation may or may not produce the soil conditions that were intended. Many times a series of tillage operations are performed in hopes that the combination will accomplish the tillage objective. The operations or combination of operations that are commonly used have evolved from years of experience. For a given area under normal weather conditions and for a given cropping system, experience has told the farmer what operations will most likely be successful. There have been improvements in the design of tillage tools (for example, we now have high-speed moldboards with trash covering devices), but farmers are still doing most of the same tillage operations as the early settlers.

How well a given tillage operation accomplishes an objective is generally evaluated by observation of the field following tillage, or more indirectly by a yield measurement of the crop grown. To aid in the evaluation of tillage operations, a basic method of soil surface measurement was developed to quantitatively describe soil surface roughness. This measure of soil condition should correlate with other soil properties. For example, the roughness of the soil surface would affect surface water storage capacity. Surface water storage in turn affects the runoff, erosion, and soil moisture content. The size and distribution of clods on the soil surface influences the seedbed and thus the ability to control weeds and obtain a stand of a given crop. Measurement of soil configuration should reflect the clod size distribution and thus be a quantitative indication of the seedbed condition. Measurement of soil surface roughness is not a direct measure of many of the soil properties modified by tillage. It should be possible, however, to relate infiltration rate, soil temperature, and soil aeration to surface roughness since thermal, liquid, and gaseous exchange occur through the surface. Finally, machine performance factors such as (1) traction, (2) ride, (3) vibration, (4) flotation, and (5) operating depth may relate to surface roughness.

Methods are available for measuring some of the soil properties mentioned, but separate measurements are required for each property. Most of the measurement methods are slow and require destructive sampling techniques. Because soil sampling is slow, the portion of a field that is sampled is generally very small relative to the total field. Bulk density, for example, is commonly determined from a few 3 inch diameter or smaller samples (2) taken from a field. Because of the variation in soil properties from location to location in a field, it is impractical to regularly measure most soil properties. Since the measurements of many soil properties require that the soil be removed from the field for analysis, it is impossible to monitor field changes in these soil properties at a given location. Finally, newly tilled or loose soils are hard to sample which makes it difficult to obtain accurate readings on these soils with current measuring methods.

Other researchers (1, 18, 19) recognized that surface configuration varied with tillage practices and used surface roughness as a parameter in evaluating the effect of different tillage operations. Various methods were used to measure the location of the soil surface relative to a given datum line or plane. Height readings were recorded at regular intervals over a given sample area. The number of readings, the spacing of readings, and size of the sample area varied, depending on the objective of the experiment. Since readings were recorded manually, the number of readings taken was influenced by the labor available to the researcher. Differences between the methods used and the results obtained indicated a need for a basic study of the measurement of soil surface roughness. Standardization of the number and spacing of readings measured in roughness studies would enable researchers to compare work done at different locations. It would also be possible to develop commercial measuring instruments if researchers were using similar methods.

OBJECTIVES

The objectives of this research were:

1. To develop an automatic data acquisition system for measuring and recording point elevations over a soil surface.
2. To develop and evaluate a method of quantitatively describing soil surface roughness.
3. To determine the quantity and the spacings of readings necessary to adequately describe soil surface roughness.

REVIEW OF LITERATURE

There has been interest in surface roughness in several fields. Researchers have studied the roughness of metal surfaces, roads, terrain, airport runways, and soil surfaces. Initially, roughness was expressed in terms of geometric properties or descriptions of geometric properties. Recently, however, there has been a trend toward use of statistical techniques in analyzing roughness.

Soil Surface Roughness

Since many soil properties that relate to the use of soil as a medium for plant growth are related to the condition of the soil surface, and since the soil surface is exposed and easy to obtain measurements upon, soil surface roughness has been used by researchers as a measure of the effect of various tillage operations.

Kuipers (17) was one of the first researchers in the agricultural field to investigate the use of soil surface roughness measurements. He developed a reliefmeter which was used to measure heights of the soil surface relative to a datum line. The meter consisted of 20 small pins spaced 10 centimeters apart and free to slide up and down in a framework. The framework was placed over the surface to be measured and the dowel pins lowered to the soil surface. The distance each dowel pin moved from the reference line to the soil surface was read to the nearest centimeter from a scale mounted behind the dowel pins. After 20 readings were taken in the initial position, the framework was moved to a different location and a new set of 20 readings was recorded. This process was repeated until 20 different sets of 20 readings were obtained. This gave a total of 400 readings over the field. Kuipers determined that the readings obtained were normally distributed and used a standard deviation approach to analyze the soil surface roughness. The 20 height readings measured at a given location were corrected for the mean of the readings at that location. The standard deviation in centimeters was then determined for the 400 corrected height readings. The base 10 logarithm of the standard deviation was determined and multiplied by 100 to give a roughness index. Roughness readings determined in this manner on fields that had been plowed or worked into a seedbed varied between zero and 100.

Kuipers and VanOuwerkerk (18) used the same reliefmeter and measurement system to obtain the total pore-space estimations in freshly plowed soil. Height readings were recorded for two rows (4 meters long and 2 meters apart) at five locations. By recording heights before the soil was tilled and again at the same location following tillage, the amount that the pore space in the plow layer changed could be estimated. Then, using this factor in combination with the pore-space values that were present before plowing, the pore space of the freshly plowed soil was determined.

Allmaras, et al. (1) also developed a random roughness index. They used a dowel pin system similar to that used by Kuipers to measure heights across the direction of tillage. Their reliefmeter had 20 pins spaced on 2 inch centers. The reliefmeter was used to measure 20 readings across the direction of tillage. Readings were taken at 20 reliefmeter settings spaced 2 inches apart in the direction of tillage, giving them 400 readings on a 40x40-inch sample area. Height readings were measured to the nearest 0.1 inch. Since earlier work by these researchers (6) indicated that the logarithms of the height readings were more nearly normally distributed than the arithmetic heights, they transformed their data by taking the natural logarithm of heights. They also adjusted the transformed readings for the column average or tillage tool orientation effect, for the row average or plot slope effect, and for the over-all average. Of the 400 readings recorded, the upper 10 percent and the lower 10 percent of the values were not used in the calculations because of the possibility of erratic height readings. An estimate of the standard error of these corrected heights was used as an index of random roughness.

Luttrell (19) expressed soil surface roughness as the sum of the absolute difference between the slopes of lines that connect the end points of successive height readings in a column taken perpendicular to the direction of implement travel. He used a profile meter developed by Schafer and Lovely (23) to obtain height readings. This meter used a single, motor-driven probe to automatically record 80 readings at one-inch intervals across the direction of tillage. The probe was driven to the soil surface and a line with length directly proportional to the distance the probe traveled was recorded on a strip chart. Because considerable time was required in manually reading distances from the strip chart, Luttrell limited his sample size to four rows of heights spaced 15 inches apart. Thus, he had 320 readings over a 60x80-inch sample area. Luttrell calculated a roughness index by summing five coefficients determined by using spacings of 1, 2, 3, 10, and 20 inches between height readings in the slope calculation.

Wilton (29) used a dowel pin type measuring instrument to study the change in level of the soil surface following tillage. He recorded one row of 60 readings spaced at one-inch increments across each plot. Measurements were taken before tillage, immediately after tillage, and at intervals following tillage to study the effect of different operations on the level of the soil surface.

Heermann (11) used an automatic probe mechanism to measure heights of the soil surface at equidistant points over an irrigation channel. Height measurements were taken at intervals of 0.0105 foot for a distance of 9.5 feet along each irrigation channel. Power spectral density techniques were utilized in the analysis of the height measurements as an aid in describing the hydraulic roughness of the irrigation channels. The roughness profiles studied did not indicate the presence of a periodic configuration.

Merva, et al. (20) discussed the use of the spectral density function to describe the frequency composition of untilled surfaces in a study of watershed surface description. They concluded that the spectral density provides insight into the spatial frequency composition of the untilled surface.

Terrain Roughness

In addition to the agricultural aspects of soil surface roughness, there has been interest in the relationship of soil surface configuration to vehicle performance. Offroad movement of construction equipment and military vehicles has caused study of terrain geometry.

VanDeusen and Hoppe (28) present a summary of the profile measurement systems that have been used in measuring terrain geometry. Measurement methods have varied from manual surveys to the use of specially constructed continuous recording instruments. For the surveying method, surveys were made along a line with point elevation readings taken at equal intervals. The technique was accurate but very slow. Most automatic profile measuring systems recorded continuous traces of the ground profile, but establishment of a reference line was a problem. The automatic measuring systems generally had a measuring wheel or ground sensor mounted on a trailer or vehicle which was moved over the area to be measured. The relative distance between the measuring wheel and the reference vehicle was recorded as the ground profile. This means that the vehicle served as a moving average type reference for the recorded data.

These terrain measurement techniques would not be applicable to measurements on a newly tilled soil because of the looseness of the soil. Also, the terrain measurement techniques were developed to measure large areas and large relief features while tillage studies require measurement of small relief features over smaller areas.

Analysis of terrain roughness data presents many of the same problems as analysis of tillage roughness data. VanDeusen and Hoppe (28) discuss the use of power spectral density, Fourier series coefficients, and the Fourier transform for studying the periodic aspects of terrain roughness. They conclude that the power spectral density function is the most promising for classification and interpretation of terrain surface profiles.

VanDeusen (27) found that roughness or profile readings were normally distributed for terrain data that were available. Under these conditions, the variance was sufficient to characterize the distribution of amplitudes of the roughness.

Stone and Dugundji (26) developed a Fourier analysis for quantifying soil surface microrelief. They divided roughness up into six measurements: (1) expected range of heights of prominent microrelief features, (2) expected height of the tallest microrelief feature, (3) expected range of slopes of prominent microrelief features, (4) tendency of microrelief features to be repetitive in form and/or spacing, (5) over-all irregularity of microrelief features, and (6) cell length, i.e., the length of curve that must be traversed to experience all significant features. These measurements relate to surface characteristics of primary interest in the design of vehicles to operate over a given terrain.

Road and Runway Roughness

Surface roughness has long been a concern in the construction and evaluation of roads. Hveem (13) presents a history of road measuring devices which have been developed over the years. Perhaps one of the first devices built was a pre-1900 instrument called the "Viagraph." This instrument was pulled along the road surface and recorded on paper a profile of the road surface in much the same manner as current profilometers which are used to measure road surfaces. Of course today's instruments are much more sophisticated than early versions, but the basic measurements have remained the same. Using recorded surface information, for many years road roughness was calculated as the inches of vertical displacement in the road surface per given distance. This description, however, gave no indication of the distribution of roughness. Recently, researchers (7, 22) have used power spectral density methods in analyzing road roughness in an attempt to better describe the periodic aspects of road configuration.

The problems in describing the roughness of airport runways are similar to those of describing road roughness. Power spectral density techniques were used by Houbolt (12) in studying runway roughness.

Metal Surface Roughness

Although the height variations on metal surfaces are much smaller than those of soil, roads, or terrain, similar techniques have been developed to describe the roughnesses. Hasunuma (10) discussed methods that have been used to analyze the surface profile of material surfaces. Continuous recording of the surface profile presented the same problems of developing a surface follower and of establishing a reference line as were experienced in terrain roughness measurement. Hasunuma also reviewed the work of several Japanese researchers and noted that they generally found surface height measurements were normally distributed. As in other areas of roughness study, autocorrelation and power spectral density techniques have been used (10, 16) to aid in the description of metal surface roughness.

DEVELOPMENT OF SOIL SURFACE PROFILOMETER

Mechanical System Specifications

Several methods have been developed for measuring the roughness of various surfaces. For firm surfaces such as roads, metals, or untilled soil, followers that can be moved over the surface have been used (3, 7). Surfaces that can be walked on without changing the surface configuration have been measured using surveying techniques (26). To measure the soil surface following tillage, however, different measuring techniques must be used. Following tillage, the soil is loose and small pressures applied to the surface will change the configuration. This eliminates the use of surveying techniques and the use of continuous recording profilometers unless a follower could be developed that exerted very small pressure on the soil surface. To measure the surface of loose soil, researchers have used dowel pin type instruments (6, 17, 29) or mechanized probe units (11, 19). These units worked relatively well, but the manual reading or recording of data required with these units greatly restricted the number of height readings that could be obtained.

Since one of the objectives of this study was to determine the number of readings necessary to describe soil surface roughness, an instrument (Figure 1) was constructed to quickly and automatically record a large number of readings. The first step in designing the soil surface profilometer was to determine the desired size of the sample area. Other researchers have used sample areas as small as 40x40 inches (6) and as large as 2x4 meters (18). The largest anticipated soil configuration of

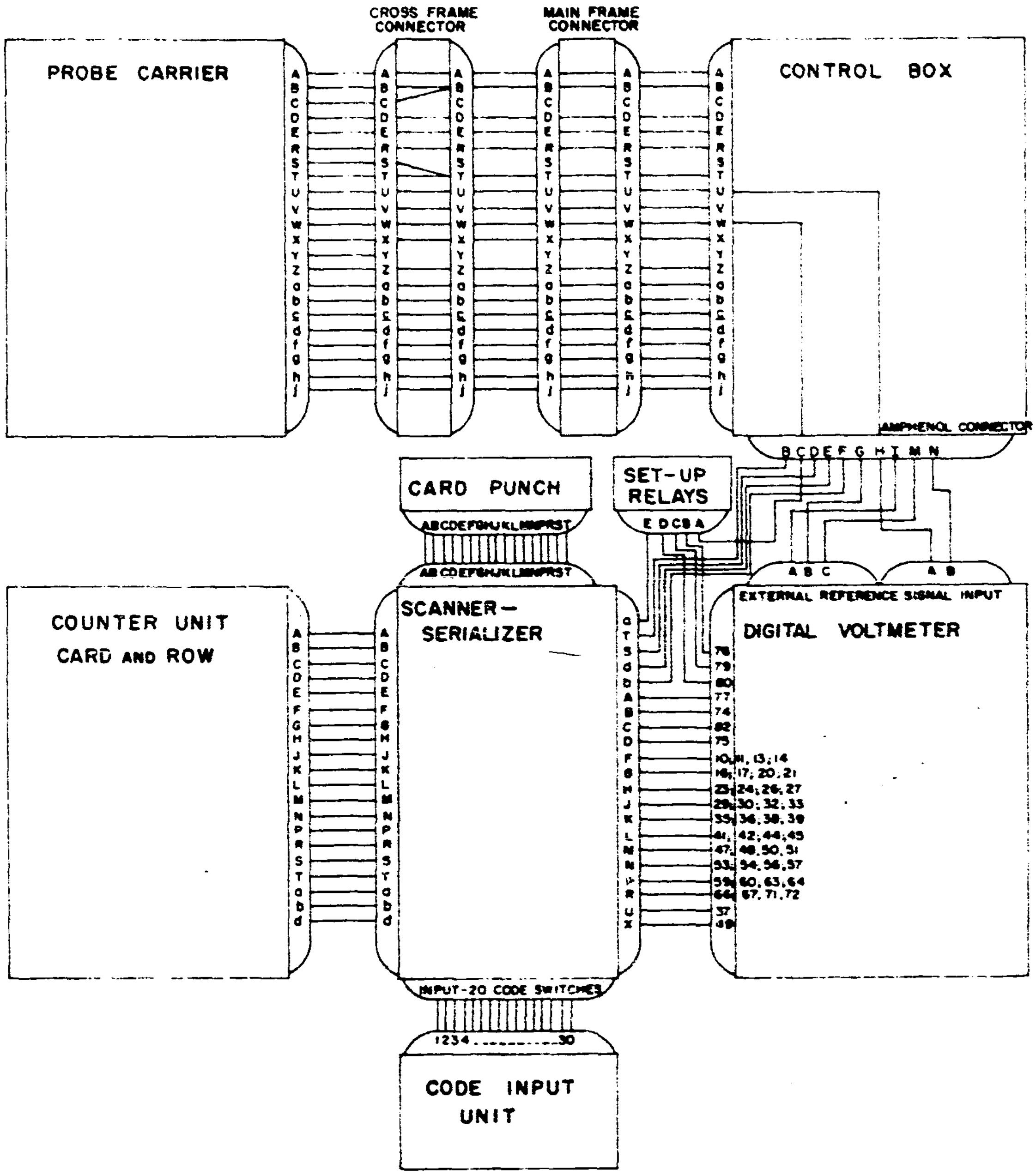


Figure 1. Profilometer, block diagram and external wiring

interest was the effect of row width (30 and 40 inches) and the associated ridging by cultivation equipment. So that two cycles of any surface configuration related to row width could be measured, a main frame (Figure 2) was designed to cover a 60x80 inch sample area. The frame was constructed of 1.41x3 inch aluminum channel. It was designed to fold for transport by removing a small bolt at each corner and pins from two corner braces. Adjustable legs with cone-shaped feet (Figure 3) were mounted at the four corners. The legs rotate within the cone-shaped feet so the feet remain fixed as the frame is raised and lowered. Bubble levels were mounted on the main frame at three corners for rapid leveling of the profilometer. This system worked very well and provided a stable base for the profilometer.

A second framework (cross frame) was constructed of the same size aluminum channel as the main frame and was mounted across the main frame. A 72-rpm synchronous motor (Superior Electric Type SS250) was used to drive the cross frame forward or backward 60 inches across the main frame. A rack and pinion arrangement (Figure 4) served as a drive train for moving the cross frame. Gears at each end of the cross frame were keyed to the axle, and the axle was driven from the right end. The components used in the cross frame drive were 1/2-inch wide, 14-1/2 degree pressure angle, 16 pitch steel rack and gears, and No. 25, 1/4 pitch rollerless chain. The cross frame drive speed was 3.5 in./sec.

A carrier framework (probe carrier) was constructed of aluminum and mounted on the cross frame. A 72-rpm synchronous motor (Superior Electric Type SS400) was used to drive the probe carrier 80 inches left or right

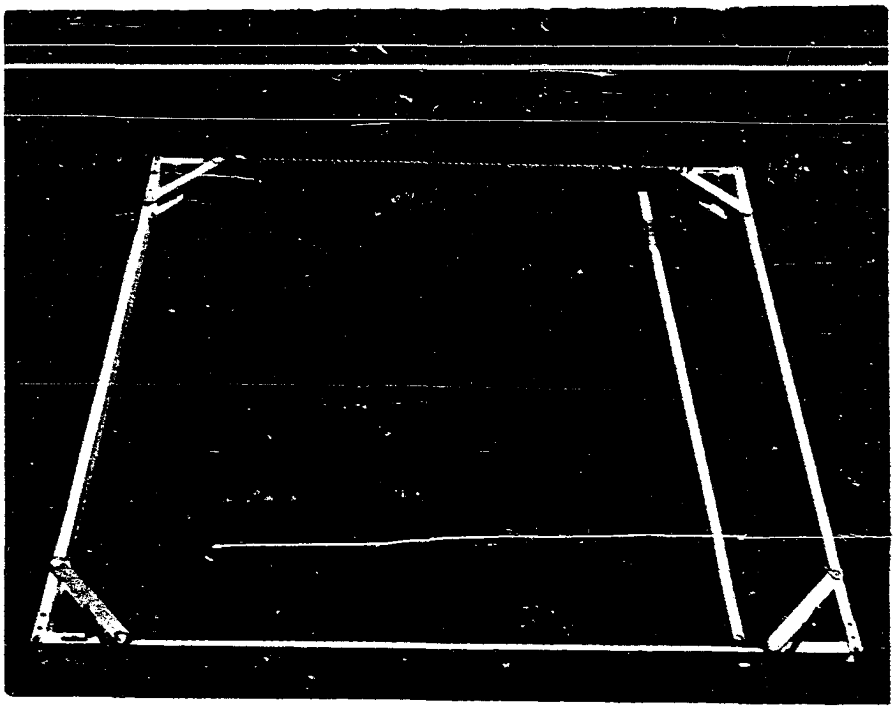


Figure 2. Main frame of profilometer

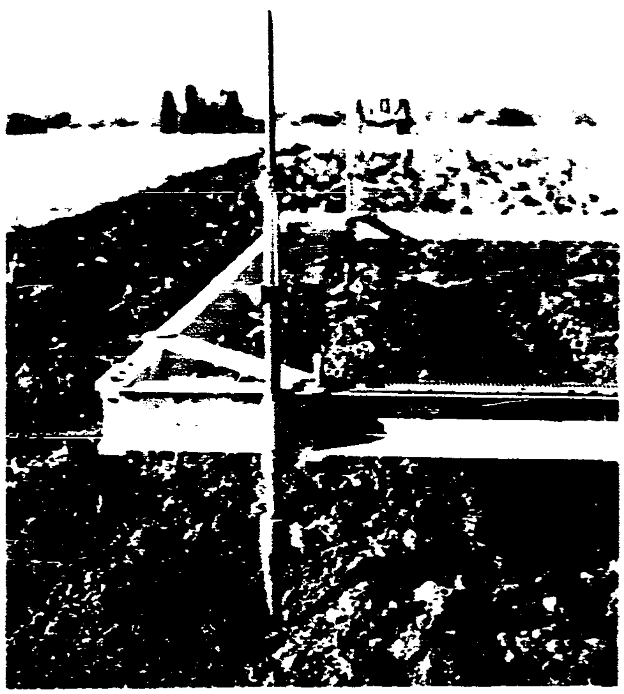


Figure 3. Leveling leg with cone-shaped foot and sighting rod

along the cross frame. The rack and pinion arrangement shown in Figure 5 was used for this drive. Gears and rack with 14-1/2 degree pressure angle, 32 pitch, and 3/16-inch width and No. 25, 1/4 pitch rollerless chain were used in the probe carrier drive. The probe carrier drive speed was 4.7 in./sec.

A motor-driven measuring probe and associated control circuitry were mounted on the probe carrier. A 72-rpm synchronous motor (Superior Electric Type SS400) with a 3-inch diameter, 3/16-inch wide, 14-1/2 degree pressure angle, 32 pitch drive pinion in combination with a rack mounted on the probe was used to drive the probe. The probe was designed to measure height differences up to 15 inches.

Self-retracting, coiled communication cord (Figure 6) was used to carry needed conductors from the main frame to the cross frame and probe carrier. Quick-disconnect connectors were used to join the cord at each frame so the framework could be easily separated into three pieces (main frame, cross frame, and probe carrier) for transport. Two men were needed to move the framework as one assembly, but one man could move the disassembled unit. The complete mechanical system of the profilometer (Figure 7) provided the following features:

1. Access to any coordinate point over a 60x80-inch area.
2. Self-contained leveling system.
3. Portability (two men when assembled, one man when disassembled).
4. Easily disassembled for transport.

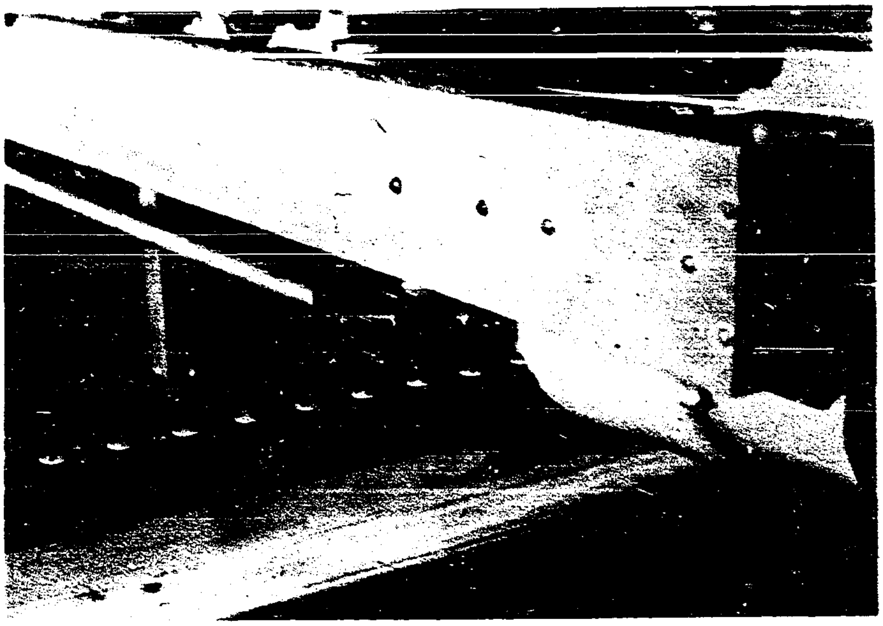


Figure 4. Cross frame drive

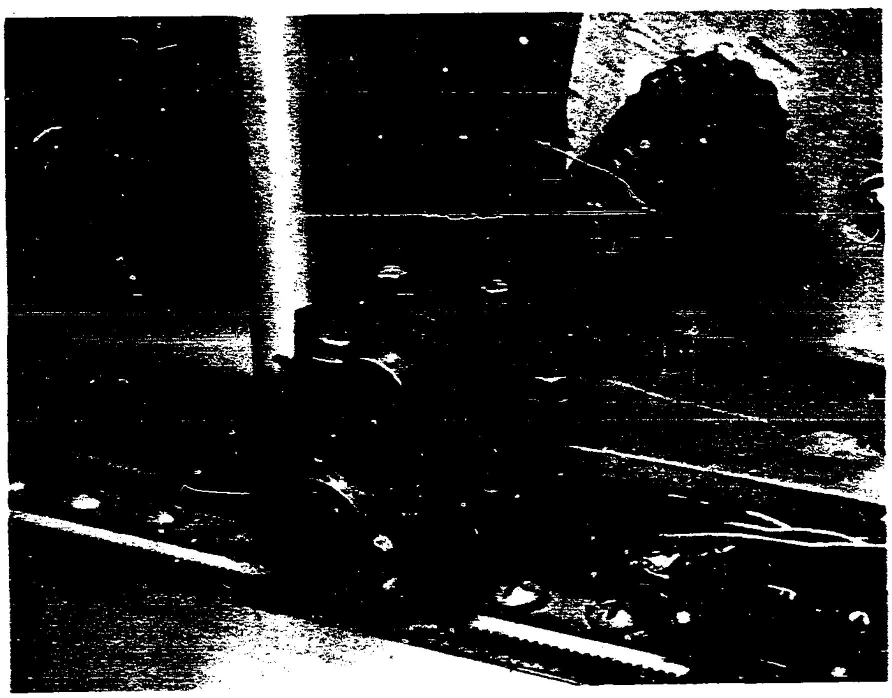


Figure 5. Probe carrier drive

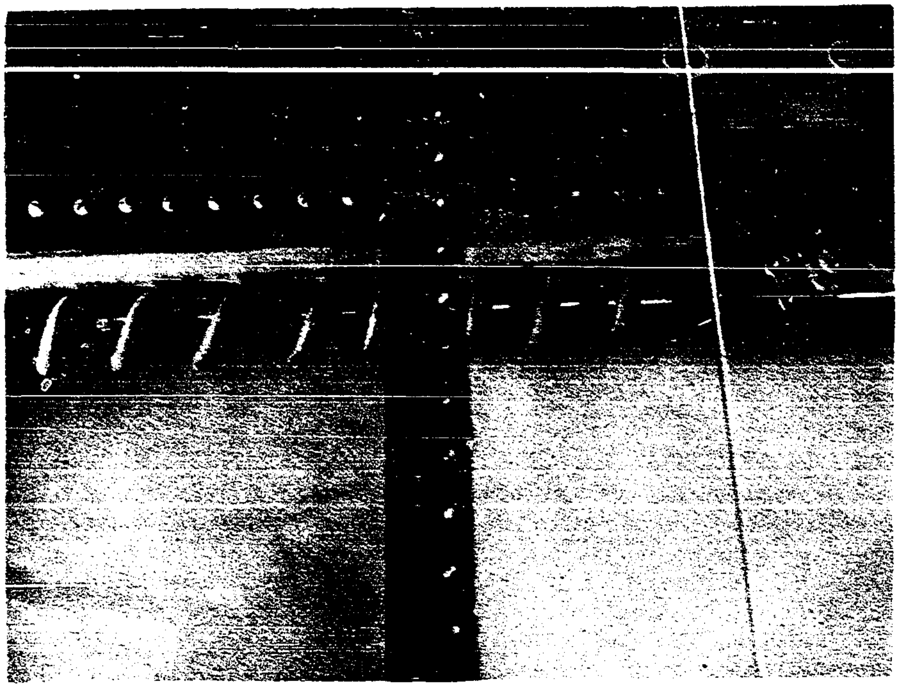


Figure 6. Self-retracting, coiled cord conductors

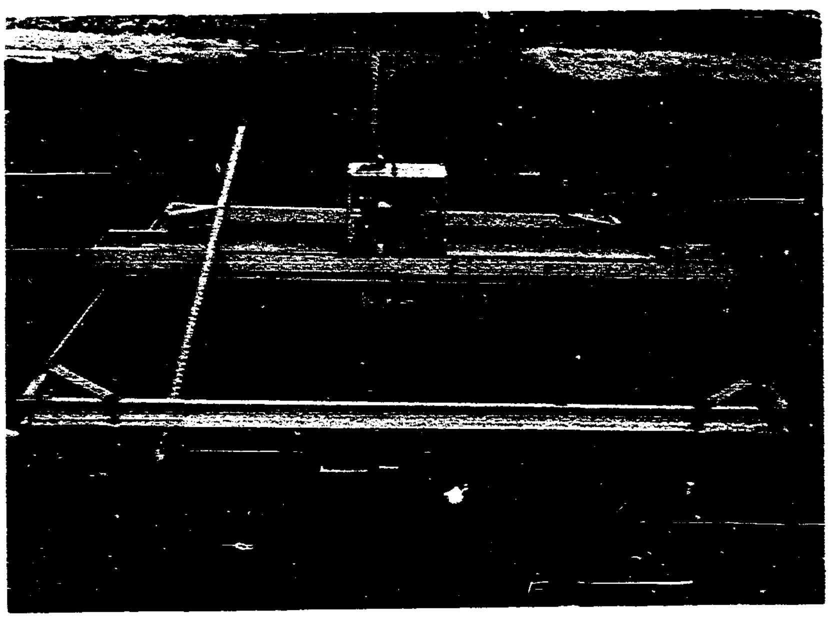


Figure 7. Assembled profilometer, mechanical system

Mechanical System Operation

Movement of the measuring probe over the sample area to preselected measurement points was completely automatic or semi-automatic. In the automatic mode of operation, the probe covered the complete sample area without stopping. In semi-automatic operation the start button had to be pushed after each row was measured. For this study, the instrument was set to take readings on one-inch increments for both the row (in the direction of tillage) and column (across the direction of tillage) directions. The one-inch spacing was selected because smaller roughness features would not appreciably affect the soil properties that may correlate with surface roughness. Also, other researchers (1, 17, 19) have had satisfactory results with one-inch and larger spacings in surface roughness measurements. Linear cams, mounted to the main and cross frames (Figure 11), controlled the location of measurement points. Truss-head machine screws were used as cam lobes at one-inch increments. Snap-action switches actuated by the cam lobes sense the probe carrier and cross frame positions and control the drive motors. Lobe screws could be placed at any location to provide various spacings of the readings.

At each measurement point, the measurement probe was driven downward until it touched the soil surface. A snap-action switch in the probe (probe bottom switch) was activated by the force of the soil surface on the movable probe end. This stopped the probe motor and initiated the recording of the distance the probe had moved. The force required to activate the switch was adjustable from 50 to 1000 grams. The force was set between 50 and 100 grams for this experiment. The higher forces would be needed to penetrate residue when measuring areas with surface residue.

In the automatic and semi-automatic operating modes, the profilometer operations were performed in the following sequence.

1. Cross frame was located on cam 1 of the main frame (reverse end); probe carrier was located on cam 1 of the cross frame (right end).
2. The probe was driven to the soil surface and stopped; distance the probe moved from its datum position to the soil surface was automatically stored by a digital voltmeter-ratiometer.
3. While the stored height reading was being automatically recorded on punch cards, the probe moved up; the probe carrier moved forward to cam 2; the probe was again driven to the soil surface and the reading recorded. This sequence was repeated until the carrier reached the 80th cam on the cross frame.
4. The probe carrier returned (moved right) to cam 1 on the cross frame; the cross frame advanced (moved forward) to cam 2 on the main frame.
5. The probe carrier again moved through the 80 readings across the cross frame, and the sequence was repeated until the total 60x80-inch sample area was covered on one-inch increments.

In addition to the automatic operation, manual controls were provided to individually move the cross frame, probe carrier, and probe. Schematic diagrams of the circuitry that control the profilometer mechanism are shown in Figures 8, 9, and 10.

Recording System

In addition to the mechanical system, the profilometer also contained an automatic data recording system. This system (Figure 12) consisted of

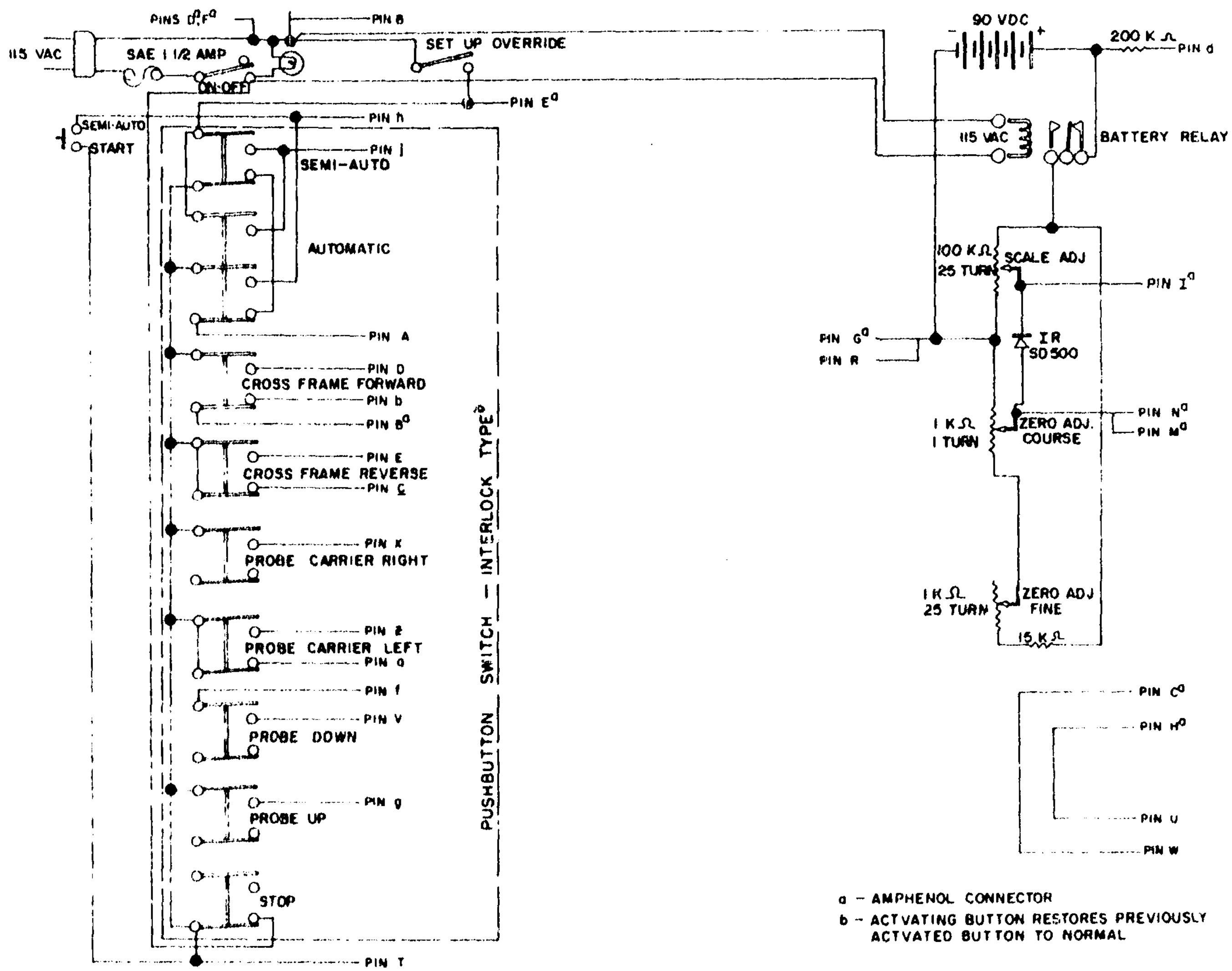


Figure 8. Profilometer control box circuitry

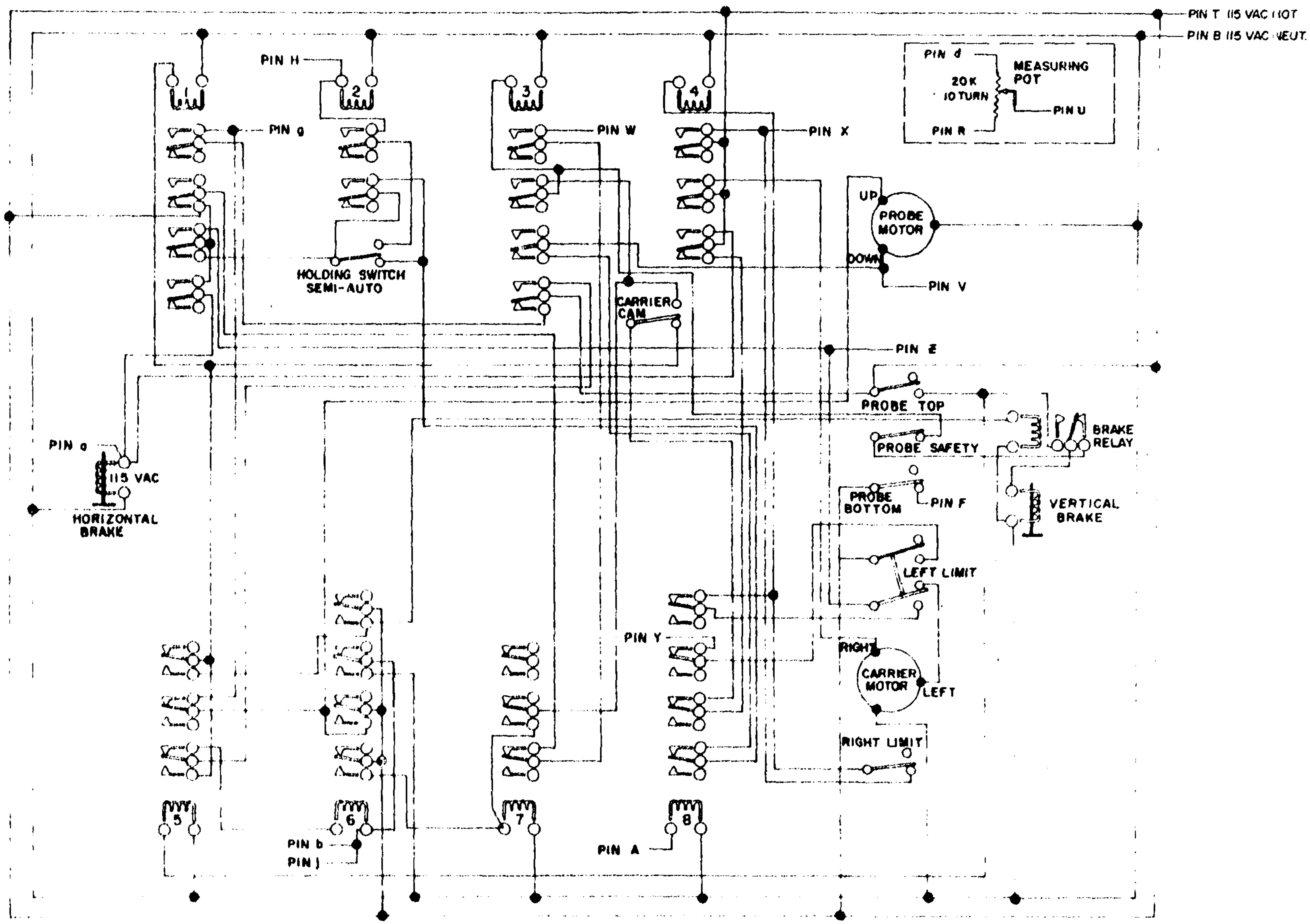


Figure 9. Profilometer probe carrier circuitry

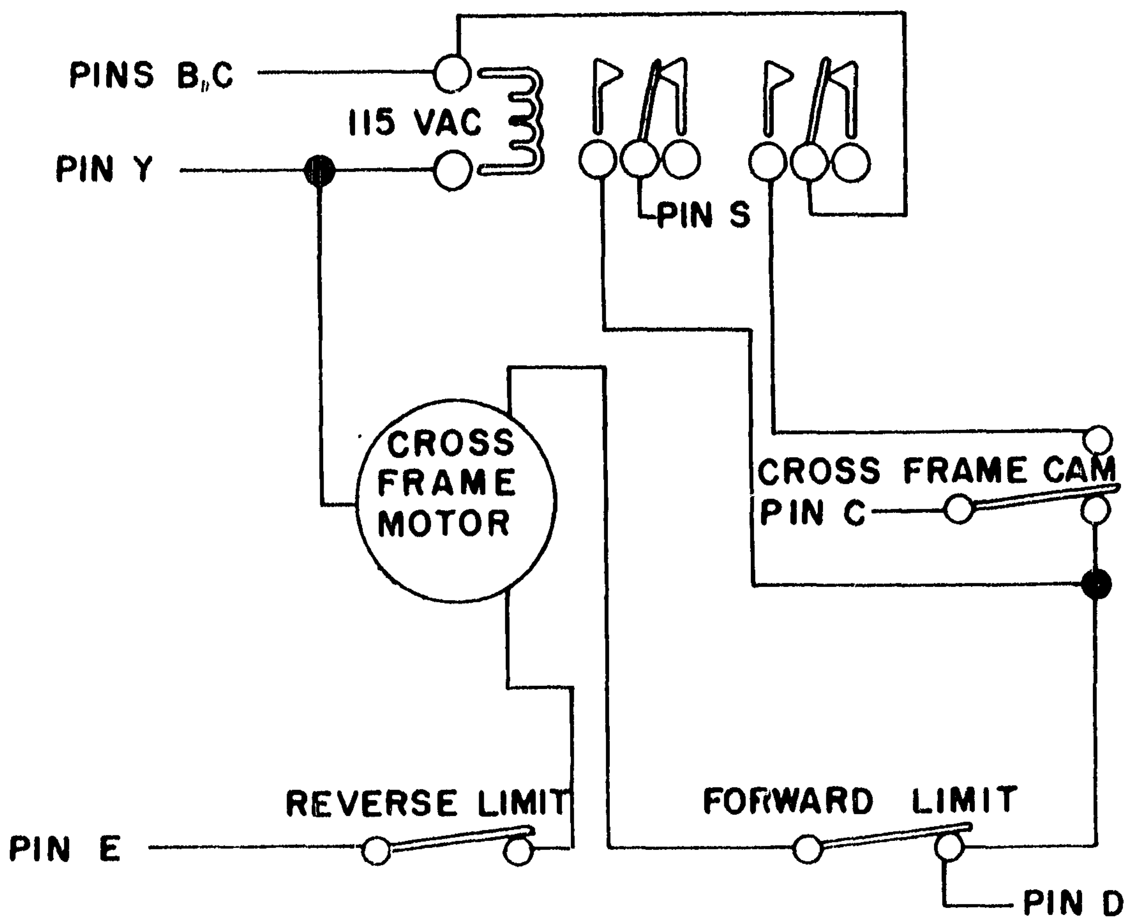


Figure 10. Profilometer cross frame circuitry

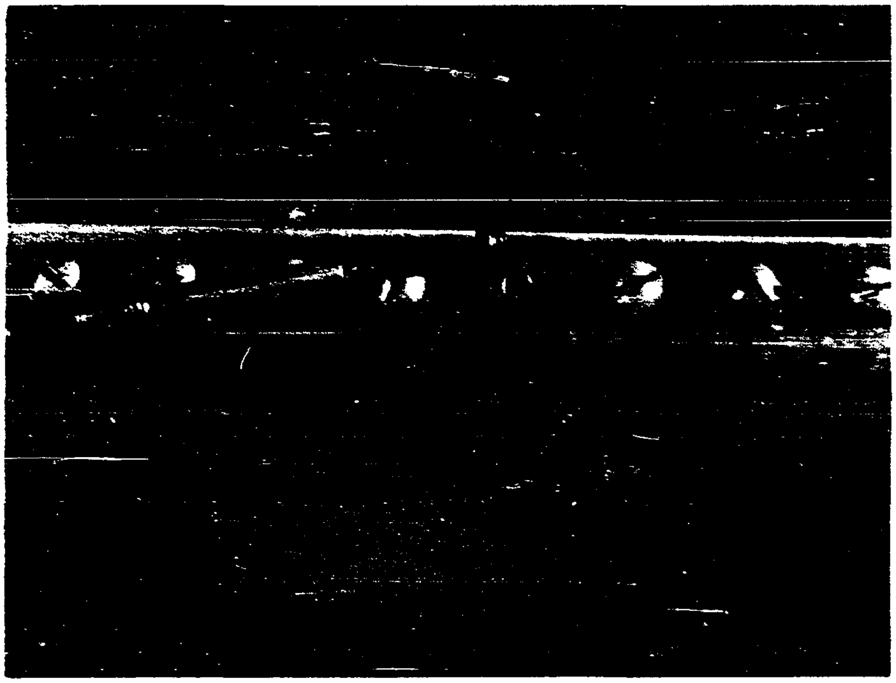


Figure 11. Linear cam with screw head lobes

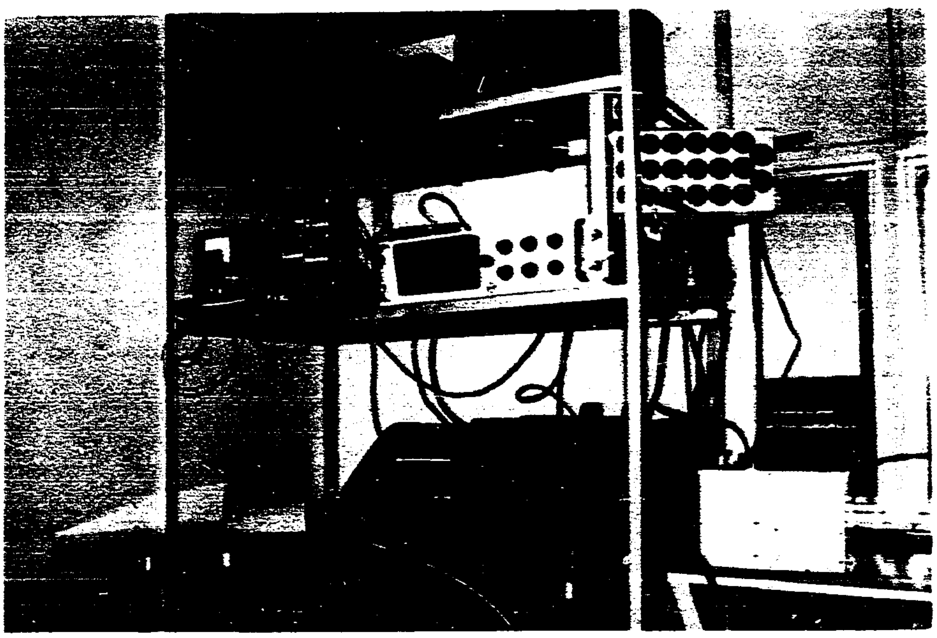


Figure 12. Profilometer data recording system

a measuring circuit, code input unit, digital voltmeter-ratiometer, scanner-serializer, and card punch.

The measuring circuit converted mechanical probe travel into an analog voltage signal. A linear resistance, ten-turn rotational potentiometer was geared to the measuring probe (Figure 16) to sense the probe travel. This potentiometer was wired in parallel with zero and scale adjustment potentiometers across a 90-volt d.c. battery. The ratio of the voltage across the measuring potentiometer to a reference voltage set by the scale adjustment potentiometer was directly proportional to the probe travel. The zero adjustment potentiometers (coarse and fine) were used to adjust the measuring potentiometer voltage input to zero when the probe was in the datum (raised) position. By adjusting the scale potentiometer, the voltage ratio was calibrated to obtain direct readings of the probe travel in the desired units. Measurement of the probe travel as a voltage ratio prevented the readings from changing as the measuring circuit battery discharged. The measuring circuit schematic diagram is included in Figures 8 and 9.

The analog voltage ratio representing probe travel distance was converted into a digital reading by an NLS model 3010 digital voltmeter-ratiometer. This reading, calibrated for this study in inches of probe travel, was transferred by a scanner-serializer to an IBM model 026 card punch. The scanner-serializer was constructed for use in this system. Commercial units are now available and should be incorporated in future systems.

The code input unit was used to record information concerning treatment, location, date, etc., on each card. The code input unit consisted of 20 rotary, ten-position switches which were wired to provide contact closures representing numbers 0 through 9. Punch coil voltage was transferred through the code switches to the proper punch coil to record the coded identification values. Code switches were set manually to the correct values before a plot was measured and the information was automatically punched in columns 4-20 of each card as the sample area was measured. Row number and card number were recorded as part of the identification code in columns 1-3. These numbers, which define the location within the sample area of each height reading, were automatically counted by a specially built stepping-switch counter unit. A schematic diagram of this counter is shown in Figure 13.

The operations of the recording system and the mechanical system were interlocked so that all operations were performed in the correct sequence. When the measuring probe stopped at the soil surface, the probe remained stationary until the voltmeter-ratiometer had read the probe travel reading. This reading was stored in the voltmeter while the probe moved to the next measurement location and the card punch punched the reading. After the reading was punched, the voltmeter then read the next reading upon command initiated by the probe bottom switch when the probe reached the soil surface at the next location. The circuitry that provided for this interlocking and sequencing of operations is shown in Figure 14.

The recording instrumentation and the profilometer control box were located inside an instrument trailer. The trailer was air-conditioned to provide temperature, humidity, and dust control within the limits required

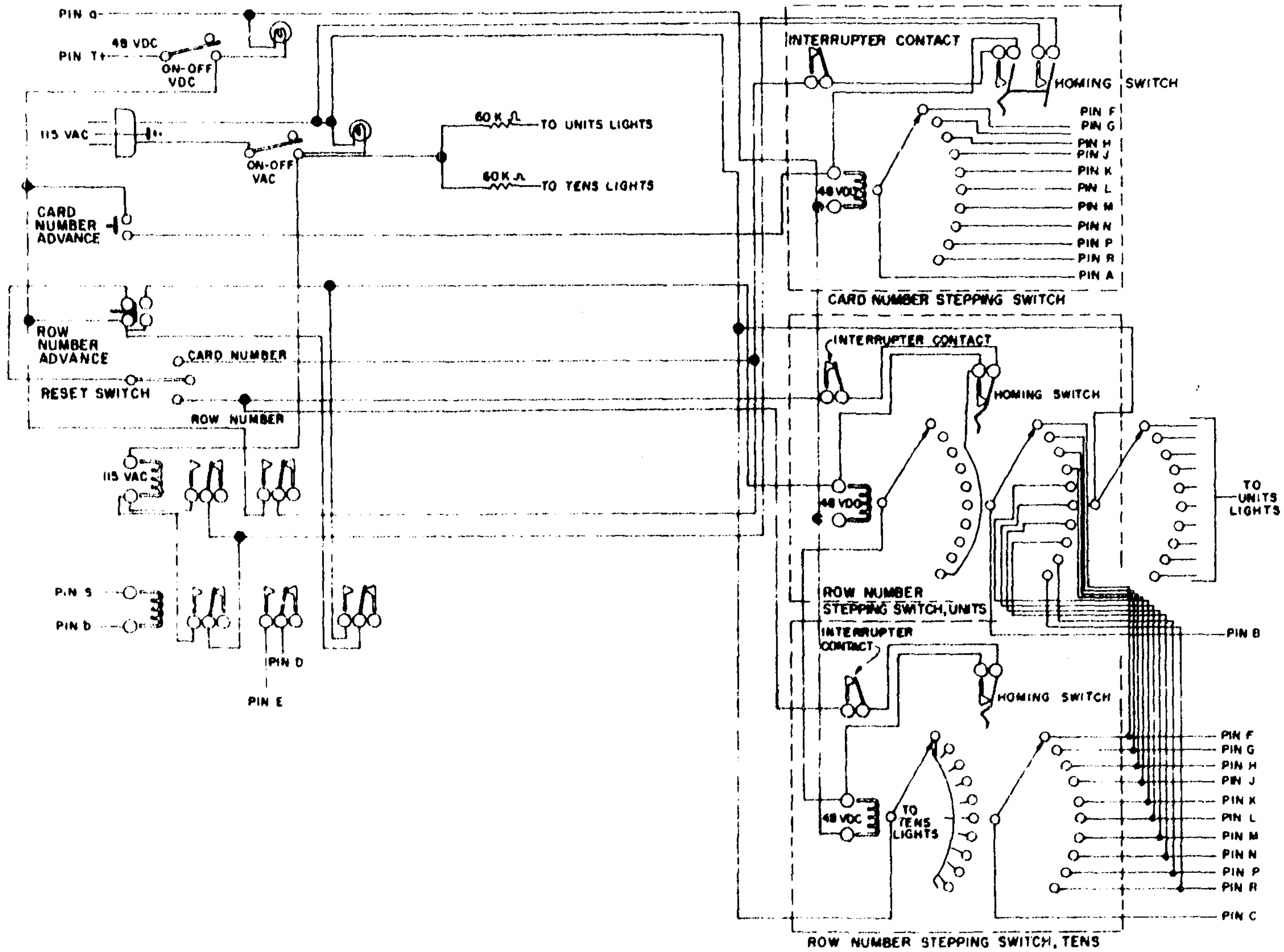


Figure 13. Profilometer card and row counter circuitry

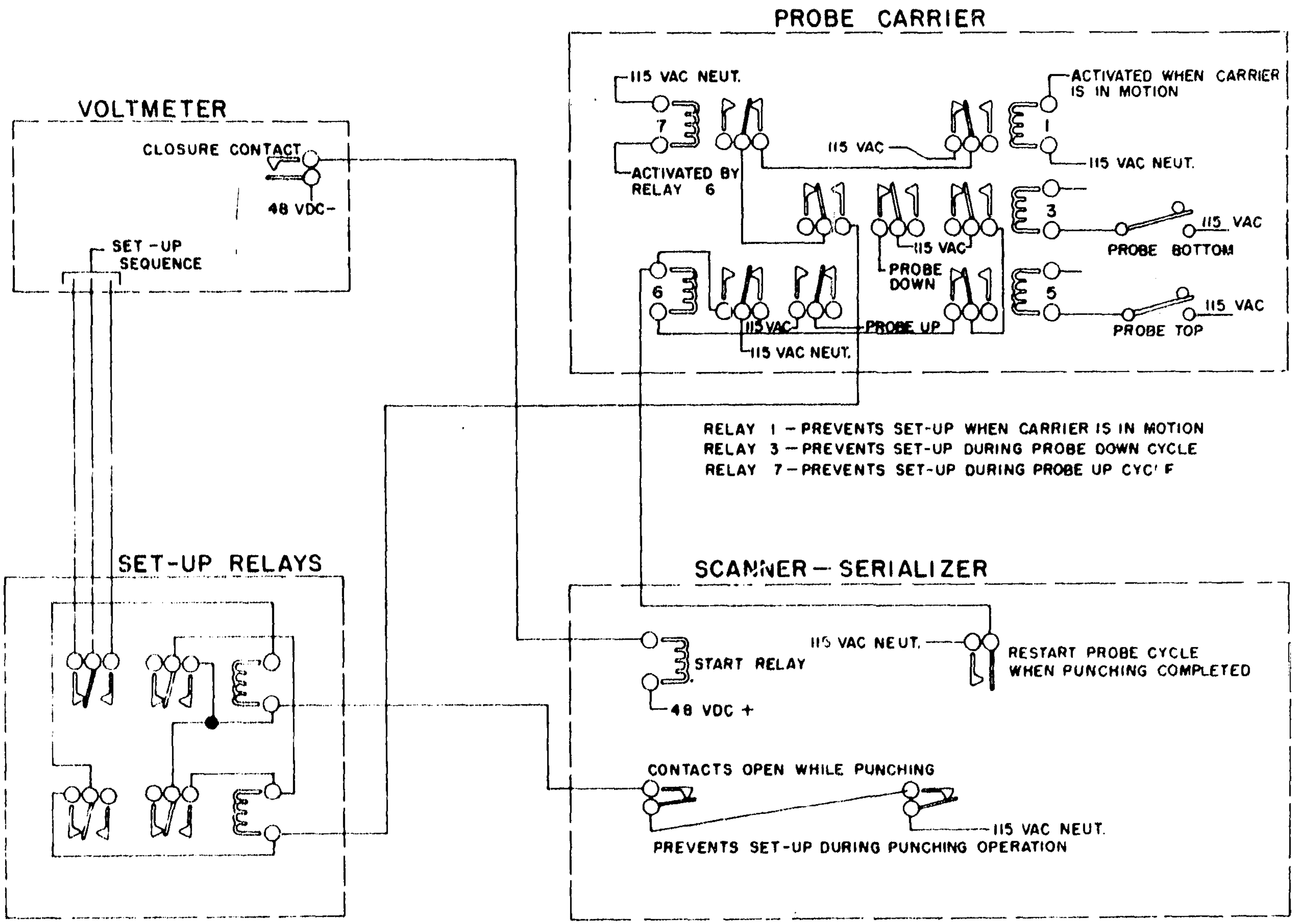


Figure 14. Profilometer interlocking circuitry

by the instruments. A portable a.c. generator provided power for the instrumentation system. A 50-v. d.c. power supply provided the d.c. voltage needed by some of the circuits.

With the profilometer, 4800 height readings were measured and recorded in 3 to 4 hours over a sample area. Time differences were caused by variation in the time required for the voltmeter-ratiometer to store the probe travel readings. If adjacent readings changed only slightly, the ratiometer stored the reading faster than if the readings changed in several digits. Probe travel readings were recorded on punch cards to the nearest 0.01 inch.

To test the accuracy of the profilometer, the unit was set up over a level, smooth surface and readings recorded. The same area was measured three times and the average reading for each location was calculated. The largest standard deviation for a set of readings was 0.0122 and the standard deviation for average readings was 0.0075. For the worst sample, 99.7 percent of the readings were within $\pm$ 0.037 inches of the mean. Thus, there was no significant sag in the framework and the profilometer was accurate in repeatedly measuring the same surface. Due to the segmented permanent-magnet construction of the probe drive motor (Superior Electric Type SS400), the probe tended to stop at the segments instead of at random points. The combination of motor construction, drive ratio, and delay in the probe brake resulted in the probe tending to stop at the nearest 0.1 inch. Therefore, profilometer readings were accurate to $\pm$ 0.05 inch.

EXPERIMENTAL PROCEDURES

Experimental Design

An experimental area was selected at the Agricultural Engineering-Agronomy Research Center near Ames, Iowa. The area selected for the study was relatively level with uniform topography. The soil was predominantly Webster silty clay loam with a few spots of Harpster loam. For over a year prior to the study, the area had been in alfalfa. The alfalfa stand was poor and wild grasses were also growing in the field. The field was drained by subsurface drainage tile located on 120 foot centers. Because of the uniformity of soil type, topography, and previous cropping practices, this area provided an excellent possibility for duplicating roughness conditions between replications of the same treatments.

A randomized block design with six replications was used for the experiment. Treatments were selected to provide a range of surface roughness common with normal tillage procedures. The treatments selected were plow (P), plow-disk (PD), plow-disk-disk-harrow (PDDH), power rotary tillage (RT), and untilled check (C). Each treatment was randomly assigned to a 20 feet wide by 90 feet long plot within each block. Thirty-foot-wide turnways separated the blocks and were used for moving equipment and tillage machinery between plots. A map of the field layout and treatment locations is shown in Figure 15.

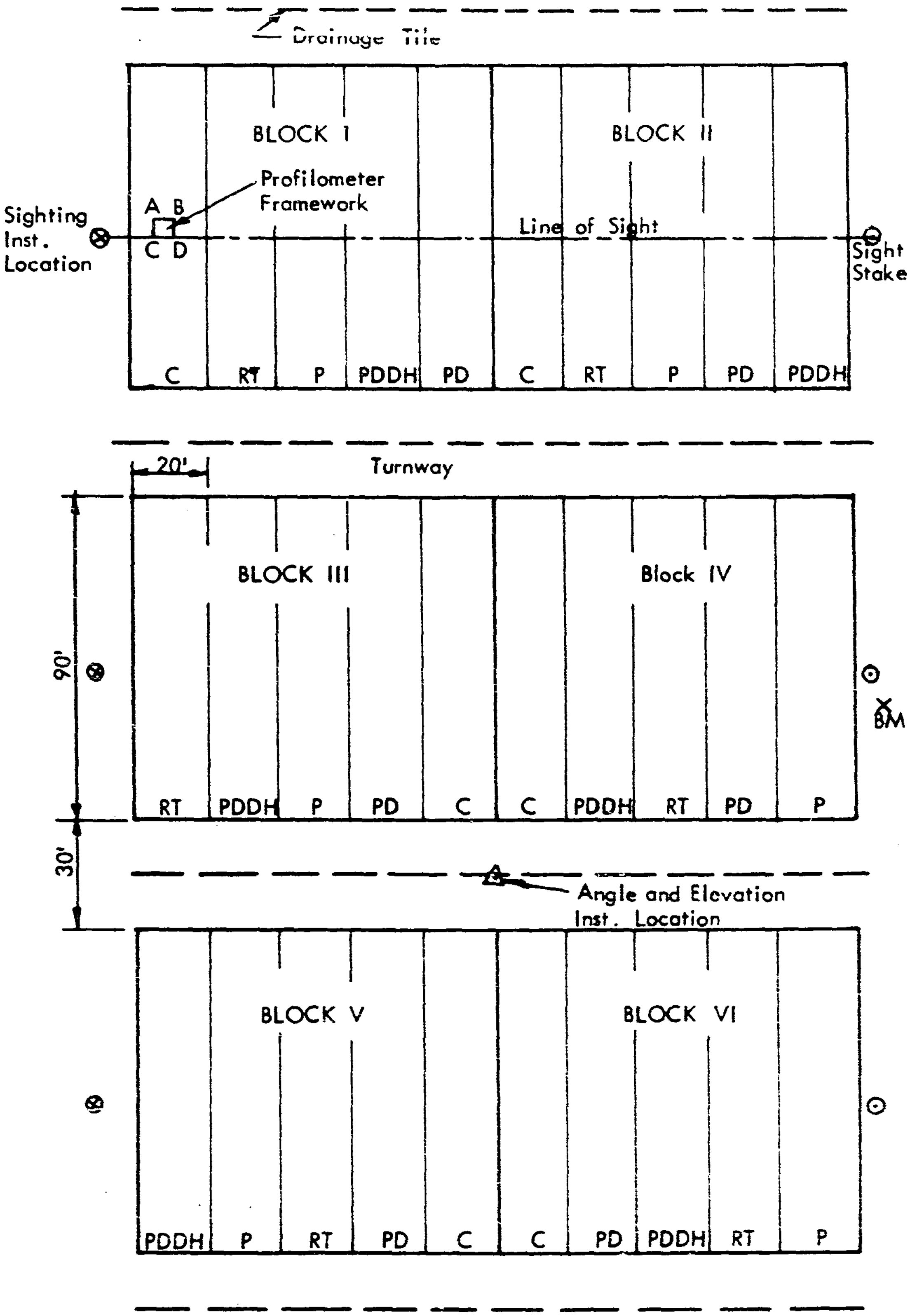


Figure 15. Field layout and surveying control locations

Before Tillage Measurements

To determine the initial condition of the soil, soil samples and soil height readings were taken before tillage. Uniform residue conditions were maintained for all plots by removing the grass in and surrounding the sample area. A flame cultivator burner was used (Figure 17) to kill the grass and burn the residue. Residue was removed from an area larger than the sample area to prevent the tillage implements from moving residue into the sample area. After the residue had been removed, soil samples were taken for bulk density determinations. Samples were taken at four random locations near the corners of the sample area. A motor-driven, soil core sampler developed by Buchele (5) was used to obtain undisturbed soil samples. The sampler, shown in Figure 20, was used to remove 3-inch diameter by 3-inch long soil cores to a depth of 15 inches. The cores were weighed, oven-dried, and the dry weight bulk density was calculated. Results of the bulk density calculations are given in Figure 18.

Following residue removal and soil sampling, the profilometer was used to obtain height readings for each sample area. The first step in this procedure was to position the profilometer framework over the sample area and record the location for future measurements. Permanent sighting instrument locations were established on one side of the field and permanent sight stakes were driven on the other side of the field directly opposite the instrument locations. One and one-half inch pipes were driven 4 feet into the ground to serve as instrument locations while steel posts driven to the same depth served as sight stakes. A pipe was also

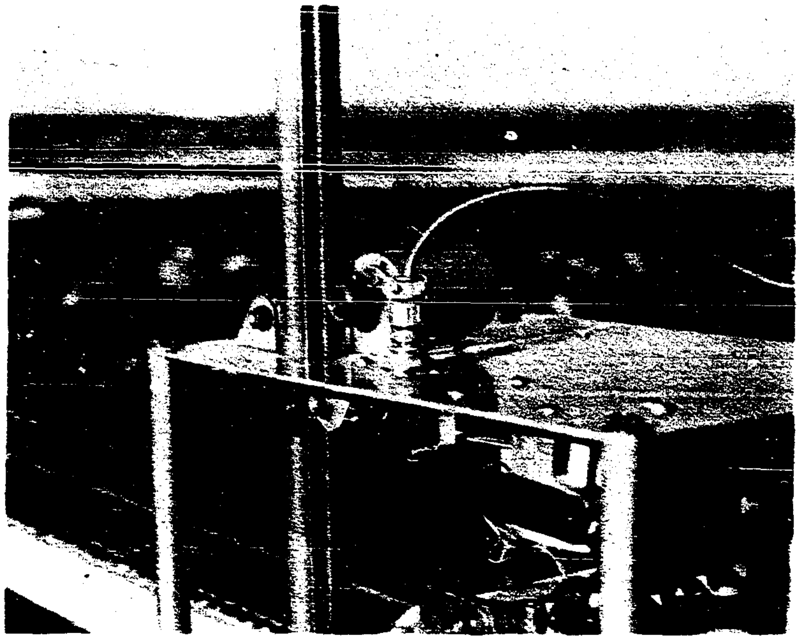


Figure 16. Probe driven measuring potentiometer

Figure 17. Burning of surface residue

TREAT-MENT	BLOCK	BULK DENSITY DEPTH 0-3"	3-6"	6-9"	9-12"	12-15"	0-6"*
RT	1	1.080	1.130	1.123	1.208	1.239	1.105
	2	1.006	1.094	1.117	1.232	1.143	1.050
	3	0.964	1.149	0.904	1.205	1.317	1.057
	4	0.990	1.068	1.124	1.128	1.219	1.029
	5	1.023	1.146	1.205	1.355	1.333	1.084
	6	1.055	1.090	1.129	1.084	1.098	1.073
PD	1	0.990	1.155	1.172	1.224	1.230	1.073
	2	1.059	1.116	1.180	1.244	1.255	1.088
	3	0.995	1.134	1.131	1.091	1.186	1.065
	4	1.072	1.192	1.188	1.223	1.257	1.132
	5	1.126	1.191	1.218	1.385	1.400	1.158
	6	1.029	1.124	1.159	1.254	1.258	1.076
P	1	1.053	1.121	1.184	1.231	1.280	1.087
	2	1.026	1.106	1.156	1.217	1.135	1.066
	3	1.015	1.115	1.196	1.235	1.311	1.065
	4	1.104	1.257	1.327	1.366	1.348	1.180
	5	1.050	1.210	1.197	1.335	1.311	1.130
	6	0.943	1.050	1.104	1.114	1.089	0.996
PDDH	1	1.041	1.178	1.164	1.151	1.189	1.110
	2	1.086	1.158	1.328	1.355	1.244	1.122
	3	1.006	1.152	1.253	1.256	1.388	1.079
	4	1.021	1.132	1.166	1.127	1.143	1.077
	5	1.020	1.159	1.179	1.291	1.368	1.089
	6	1.034	1.084	1.079	1.175	1.222	1.059
C	1	1.049	1.132	1.149	1.254	1.316	1.091
	2	1.076	1.148	1.222	1.244	1.260	1.112
	3	0.941	1.058	1.104	1.107	1.174	0.999
	4	1.018	1.152	1.163	1.141	1.238	1.085
	5	1.126	1.234	1.292	1.440	1.406	1.180
	6	1.127	1.222	1.222	1.392	1.371	1.174

* MEAN OF 0-3" AND 3-6" BULK DENSITIES

Figure 18. Bulk densities before tillage

used to establish a permanent instrument location for measuring angles and elevations. A permanent bench mark was established near the field by burying a 4-inch by 5-foot concrete post. Using the permanent markers, a line of sight could be established across the blocks with a transit and an angle could be measured from the permanent sight stakes to any point along the line of sight. The profilometer framework was located along the line of sight by aligning the sighting rods mounted on top of the leveling legs (Figure 3) with the line of sight. The framework was centered on each plot along the line of sight by measuring from the edge of the plot. The exact location of the framework along the line of sight was then determined with the angle and elevation instrument by measuring the angle between the sighting stake for that block and the sighting rod at corner C of the framework (see Figure 15). This angle was recorded so the instrument framework could be relocated at the same position following the tillage treatment. The framework was set level as indicated by the leveling bubbles on the main frame. The level was then checked at the four corners by using the angle and elevation transit. The elevation of the profilometer framework relative to the permanent bench mark was determined by measuring the difference in elevation between the main frame and the bench mark. This difference was set on the code identification unit and recorded on each card for use in describing soil level changes. After the profilometer framework was positioned, 4800 initial elevation readings were measured and recorded on a 1-inch grid over the 60x80-inch sample area. This process of sampling, frame location, and measurement was used for each of the 30 plots.

After Tillage Measurements

Following initial measurements, the tillage treatments were applied and final soil height measurements were made. In order to maintain the most uniform conditions within treatments, the following sequence was used in performing the tillage operations and obtaining the height measurements. First, a given plot was tilled. The depth of the primary tillage was measured during tillage at random locations along the furrow in the sample area. Twelve random depths were measured for the plots which were plowed and five random depths were measured in the powered rotary tillage plots. Immediately after tillage, four soil moisture samples were taken at random from the tilled layer immediately surrounding the sample area. The average moisture contents were calculated on a dry weight basis. The average depths of the primary tillage and the average moisture percentages are given in Figure 19. The profilometer framework was then relocated over the sample area and height measurements were recorded. While these height measurements were being recorded, the plots that were to receive the same tillage treatment in the other blocks were covered with 20x20-foot clear plastic sheets. The plots were left covered until just before they were tilled. The plastic cover prevented the addition of water from rains and helped to maintain equal moisture conditions at the time of tillage for a treatment in all blocks. Possible variation in moisture content between treatments was not of concern since the study objective was to describe soil roughness and not to compare tillage tool performance. After the height measurements were completed on a plot, the same treatment was applied and measurements were

Treatment	Block	Tillage depth (inches)	Moisture content (percent)
RT	1	2.8	18.3
	2	3.2	19.0
	3	2.7	18.2
	4	2.6	17.3
	5	2.9	17.3
	6	2.8	15.6
PD	1	7.5	29.8
	2	7.9	23.8
	3	8.1	28.7
	4	7.3	24.5
	5	6.7	32.3
	6	6.6	32.8
P	1	7.9	25.2
	2	7.9	26.9
	3	7.8	27.2
	4	7.2	27.1
	5	6.4	30.7
	6	6.9	--
PDDH	1	7.2	28.4
	2	--	--
	3	7.7	24.2
	4	7.8	27.0
	5	6.8	25.2
	6	7.0	29.4

Figure 19. Average depths of primary tillage and average moisture content of tilled soil

taken in another block. When the measurements for a treatment had been completed in all blocks, the same sequence was repeated to collect data for a different treatment.

The after-tillage height measurements were taken over the same sample areas as the before-tillage measurements. Following application of a tillage treatment, the profilometer framework was relocated in the same position as used for the before-tillage measurements. This was done by locating the main frame along the line of sight so the angle between the sighting stake and the sighting rod at the C corner of the framework had the same value as measured at the initial framework setting. Because the tilled soil made it hard to slide the framework to the exact position required, 4-inch diameter stakes were driven for the four framework legs to sit on. The framework could be slid on these stakes to the exact position required and locked into position by driving the cone feet slightly into the top of the stake. While the height readings were being recorded for one plot, the next plot was tilled and the corner stakes were driven. The corner stakes would not be required if the framework was not being relocated over a specific area.

Treatments were applied using full-sized farm equipment. A three-bottom, 14-inch moldboard plow was used for all plowing. A three-point hitch, 5-foot-wide power rotary tiller was used for the rotary tillage treatment. Because the sample area was also 5 feet wide, two passes were made with the rotary tiller over the sample area with the junction between the two passes located in the center of the sample area. The disk and harrow were wider than the 60-inch sample area so these operations were done in one pass centered over the sample area.

Summarizing the procedure used in obtaining experimental data, residue was removed from the sample area and soil samples were taken for bulk density determinations. The height of the soil surface was measured on a 1x1-inch grid over a 60x80-inch sample area for each plot. A tillage treatment was then applied and height measurements recorded over the same sample area that was measured before tillage. The measurements on a given treatment were completed in all blocks before any measurements were made on a different treatment.

Profilometer Measurements

The soil height readings were automatically measured and recorded by the profilometer measurement system. Before measurements were taken on a plot, the profilometer probe movement was calibrated in inches. The base position of the probe was set to zero inches. The zero and calibration were checked before each plot was measured and were rechecked immediately following completion of measurements on each plot. To speed calibration, a fixed bar was mounted on the profilometer probe carrier (Figure 21) to serve as a stop for the probe bottom switch. The distance from the zero probe position to the calibration bar was known and the profilometer could be rapidly calibrated by setting the profilometer to read the correct calibration distance. The calibration was also checked manually at 1-inch increments of probe travel.

The profilometer automatically recorded height readings and code information on punched cards. The format that was used in recording this

Figure 20. Soil core sampler

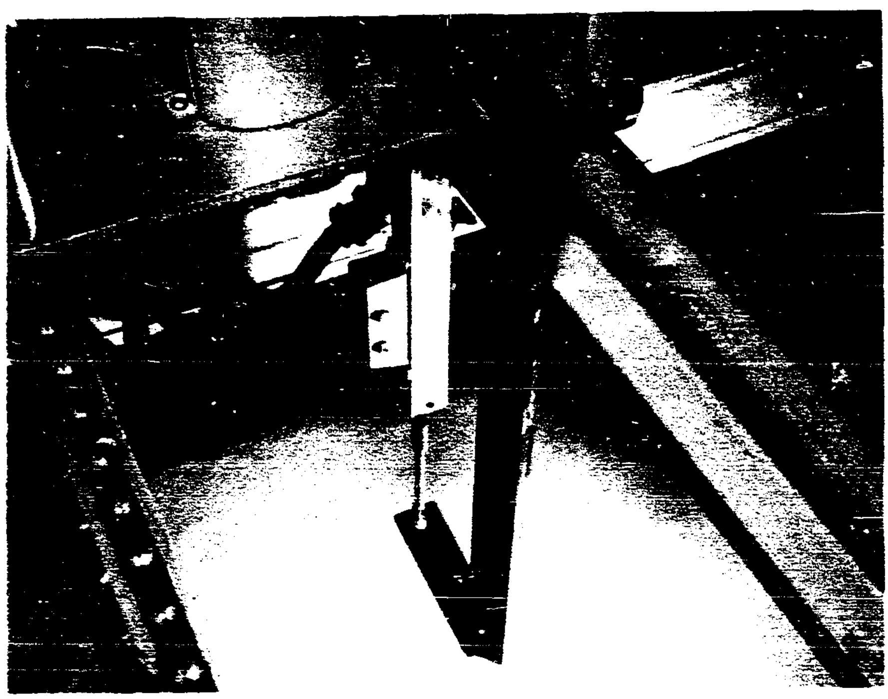


Figure 21. Calibration bar mounted on profilometer probe carrier

data on punched cards is given in Figure 22. Code information was punched in columns 1 through 20 of each card. The treatments were coded as follows:

1 - power rotary tillage

2 - plow, disk

3 - plow

4 - plow, disk, disk, and harrow

5 - untilled check.

The card number was counted automatically by the profilometer system and recorded on each card. For a given row of data, seven cards (numbered consecutively from 1 through 7) were punched. Twelve height readings were recorded on the first six cards, and eight height readings were recorded on the seventh card. The card number counter reset automatically to 1 after a row of data had been recorded, and the sequence was repeated for the next row of 80 readings. The elevation between the frame and the bench mark was recorded to the nearest hundredth of a foot. The decimal point was not punched. Field and location number codes were used to identify plot areas on the farm. The volume of cards required to record the data was large so the data were transferred from the cards to magnetic tape. The magnetic tape was used as the input to a digital computer for roughness calculations.

Punch Card Column Number	Item
1	Card number
2-3	Row number (01 - 60 rows)
4	Block number (1-6 blocks)
5-6	Treatment number (01-05 treatments)
7	Sign of elevation (1 indicates profilometer frame above bench mark; 0 indicates below)
8-10	Difference in elevation between frame and bench mark (-.-- feet)
11-12	Field or location number
13-18	Date (month, day, year)
19-20	Profile sequence (00, readings before tillage; 01, readings after tillage)
21-25, 26-30, ····, 76-80*	Distance between profilometer frame and soil surface (00-.-- inches)

*Last reading is in columns 56-60 on card number 7 of each row.

Figure 22. Format of profilometer data on punched cards

RESULTS AND DISCUSSION

Distribution of Height Readings

Before selecting analytical procedures for analyzing soil surface roughness, the distribution of the height readings was studied. The statistical procedures used to determine surface roughness indices will be influenced by the distributions. Burwell, Allmaras, and Amemiya (6) reported evidence for using a logarithmic transformation for their soil height data. Other researchers in the field have not used normalizing transformations.

As a visual check on the distribution of heights, a histogram was drawn for each plot. The height readings were corrected for field slope by fitting a plane through the data using linear multiple regression (see Calculation of Surface Roughness Indices, Standard deviation methods). The deviation of each height reading from the plane of best fit was determined. These height deviations (residuals) were grouped into 0.2 inch height classes. One height class was centered on the mean which equals zero for the residuals from multiple regression. Sufficient classes were added above and below the center class to include all height residuals for each plot. Using a digital computer, the class frequencies (number of residuals within each height class) were determined. The height classes and class frequencies were used to draw a histogram for each plot. The histograms (Appendix A, Figure 39) visually appear to represent normally or near normally distributed data.

As an additional check on the data distribution, the percentage of the total height residuals in each height class were compared to the percentage of readings that would be expected in each class for a normal distribution. Using the mean and standard deviation calculated for each plot, the percentage of readings that would occur within each class for the standard normal distribution was determined. The difference between the experimental and theoretical percentages was calculated for each height class. The maximum difference between the experimental and theoretical percentages was 6.2 percent. Of the total of over 1000 height classes represented in the histograms, the difference between experimental and theoretical percentages exceeded 2 percent in only 20 of the classes. The five largest differences for each plot are given in Appendix A, Figure 40. These results indicate a similarity to the normal distribution. The large differences between experimental and theoretical class frequencies were for height classes located both above and below the mean and at various distances from the mean. This indicates the departure from normality was random and the distribution would not be improved by a uniform transformation of the data.

As a final check of the distribution, the Kolmogorov-Smirnov test of goodness of fit was applied. The maximum differences between the theoretical normal cumulative distribution function and the experimental sample cumulative distribution function for each plot are given in Appendix A, Figure 42.

Critical (rejection) values were not available for testing the statistical significance of Kolmogorov-Smirnov differences for the distribution of residuals from regression. The critical values expected for the distribution of residuals would be somewhat smaller than the tabulated values for the distribution of uncorrected data. Since the tabulated critical value for 4800 observations at the 0.01 significance level is 0.024, normality would be rejected for at least 20 of the plots.

Because of the large number of readings, statistical rejection of normality was not surprising. With 4800 observations, the expected critical value would be very small. Uniformly distributed measurement errors, even though small, could cause rejection of normality. Although the maximum difference was significant for 20 of the plots, most of the approximately 4800 differences for any given plot were well below the 0.024 critical value. These results, in addition to the observations on the histograms, indicate that an assumption of normality was reasonable for the height residuals from regression.

The same tests as those applied to the height residuals were also applied to the original data. The height readings were corrected for the mean of each plot. Histograms were drawn and the class frequencies compared to the theoretical normal distribution. Also, cumulative distribution functions were calculated as was described previously. The results of these analyses are included in Appendix A, Figures 41 and 42. Although some differences from normality were greater for the mean corrected data than for the residuals from multiple regression, no evidence was found to indicate the advisability of a data transformation.

Calculation of Surface Roughness Indices

Other researchers (1, 17, 19) have measured soil heights and determined surface roughness indices. The roughness indices that these researchers used were included as methods of describing surface roughness in this study. The roughness indices which resulted from the various computational procedures were compared to determine the merits of each index.

Slope method

The slope method of calculating a surface roughness index refers to the method developed by Luttrell (19). He calculated a roughness index by summing the absolute difference between the slopes of lines that connect the end points of successive height readings. Using this procedure, a surface roughness index (RM) was calculated for each plot using the uncorrected height readings. Uniform field slope does not affect the RM index so correction of the height readings for slope was unnecessary.

Roughness coefficients were calculated for each column of data measured across the direction of tillage implement travel by summing the absolute differences in the slope between the end points of selected, equally spaced height readings. For this study, there were 80 columns of data with 60 height readings in each column. For each column of readings, a coefficient R was calculated as

$$R = r_1 + 2r_2 + 3r_3 + 10r_{10} + 20r_{20} .$$

The value of r_i was calculated for each column as follows:

$$r_1 = \left|\frac{(h_1-h_2)}{1} - \frac{(h_2-h_3)}{1}\right| + \left|\frac{(h_2-h_3)}{1} - \frac{(h_3-h_4)}{1}\right|$$

$$+\ldots+\left|\frac{(h_{58}-h_{59})}{1} - \frac{(h_{59}-h_{60})}{1}\right|$$

or,

$$r_1 = \left|(h_1 - 2h_2 + h_3)\right| + \left|(h_2 - 2h_3 + h_4)\right| + \ldots + \left|(h_{58} - 2h_{59} + h_{60})\right|$$

where,

$h_1, h_2, \ldots, h_{60}$ = first through the sixtieth height readings in a given column.

The terms r_2, r_3, r_{10}, and r_{20} were calculated as follows:

$$r_2 = \frac{1}{2}\Big[\left|(h_1 - 2h_3 + h_5)\right| + \left|(h_3 - 2h_5 + h_7)\right|$$

$$+ \ldots + \left|(h_{57} - 2h_{59} + h_{60})\right|\Big]$$

$$r_3 = \frac{1}{3}\Big[\left|(h_1 - 2h_4 + h_7)\right| + \left|(h_4 - 2h_7 + h_{10})\right|$$

$$+ \ldots + \left|(h_{55} - 2h_{58} + h_{60})\right|\Big]$$

$$r_{10} = \frac{1}{10}\Big[\left|(h_1 - 2h_{11} + h_{21})\right| + \left|(h_{11} - 2h_{21} + h_{31})\right|$$

$$+ \ldots + \left|(h_{41} - 2h_{51} + h_{60})\right|\Big]$$

and

$$r_{20} = \frac{1}{20} \left[\left|(h_1 - 2h_{21} + h_{41})\right| + \left|(h_{21} - 2h_{41} + h_{60})\right| \right]$$

Coefficients (R) were calculated for the 80 columns in each plot and averaged to obtain the mean roughness index for the plot (RM). The symbol (RMB) represents the roughness index calculated from the measurements taken before tillage, and (RMA) represents the roughness index calculated using the after tillage measurements. A measure of the change in soil surface roughness due to application of the tillage treatments was given by the difference between the magnitude of the index before and after tillage, (RMD). The values of (RMB), (RMA), and (RMD) are given in Figure 23. The computer program used for the calculation of the slope method indices is listed in Appendix D.

Log-normal method

The log-normal method of calculating a surface roughness index was developed by Allmaras, et al. (1). This index (RL) was calculated in the following manner. First, the height readings were transformed by taking the natural logarithm of the heights. Then, the height readings were corrected for the row effect and column effect. These corrections removed the variation due to slope and oriented tillage tool marks. Arithmetically, the corrected height readings were expressed as:

$$e'_{ij} = \ln h_{ij} - (\overline{\ln h_{.j}} - \overline{\ln h_{..}}) - (\overline{\ln h_{i.}} - \overline{\ln h_{..}})$$

where

e'_{ij} = corrected height readings in the $i^{\underline{th}}$ row and the $j^{\underline{th}}$ column

TREAT-MENT	BLOCK	ROUGHNESS INDEX (INCHES) BEFORE TILLAGE (RMB)	AFTER TILLAGE (RMA)	DIFFERENCE (RMD)
RT	1	21.2	150.8	129.6
	2	15.2	92.3	77.0
	3	19.5	94.8	75.3
	4	21.0	100.2	79.2
	5	16.6	102.0	85.3
	6	18.3	113.1	94.8
PD	1	14.3	113.7	99.4
	2	15.6	114.5	99.0
	3	16.3	119.2	102.9
	4	12.8	111.6	98.7
	5	16.6	144.0	127.4
	6	17.3	128.1	110.9
P	1	16.7	154.0	137.3
	2	17.8	172.4	154.6
	3	18.4	154.4	136.1
	4	13.9	131.3	117.4
	5	14.5	153.8	139.3
	6	18.3	147.8	129.5
PDDH	1	18.7	100.9	82.3
	2	****	*****	*****
	3	18.5	118.8	100.3
	4	19.8	88.5	68.7
	5	15.7	96.2	80.5
	6	19.4	100.2	80.8
C	1	19.2	17.1	-2.1
	2	15.0	14.7	-0.3
	3	16.7	14.2	-2.5
	4	17.7	14.2	-3.5
	5	17.4	15.4	-2.1
	6	23.0	23.0	-0.0

Figure 23. Roughness values calculated using slope method

$\overline{\ln h_{.j}}$ = average of the transformed readings in the j^{th} column.

$\overline{\ln h_{i.}}$ = average of the transformed readings in the i^{th} row.

$\overline{\ln h_{..}}$ = over-all average of the transformed readings.

The $\overline{\ln h_{..}}$ was retained in the corrected height readings to avoid negative numbers in later computations.

The corrected height readings were sorted into ascending order and the upper and lower 10 percent were eliminated from the calculations to remove erratic height readings. The remaining corrected height readings were used to estimate the standard deviation for each plot. Upper limits were established for the corrected heights and the proportion of e'_{ij} values with magnitudes less than or equal to the upper limits was determined for each upper limit. The first upper limit used was the smallest e'_{ij} value. Succeeding upper limits were established by adding 0.005 times the range of e'_{ij} to the preceding upper limit. The normalized fraction (proportion) undersize (Y') was estimated for each calculated fraction undersize (Y) by a digital approximation solution for:

$$Y' = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z_k} e^{-(Z^2/2)}\, dZ$$

where,

$$Z_k = (Y - 0.5) \,/\, \sqrt{Y(1-Y)} \;.$$

The standard deviation was estimated from the best linear fit ($Y' = \alpha + \beta e'_{ij}$) of the points between 0.10 and 0.90 fraction undersize in a plot of normalized fraction undersize versus the corrected heights. The standard deviation among logarithms of heights was calculated as $0.34/\beta$, where β was estimated from the data fit and 0.34 was the fractional area under the normal curve for one standard deviation from the mean. These estimated standard errors among height readings were expressed in inches and were used as an index of random surface roughness.

Results of the calculation of the log-normal roughness index are given in Figure 24. The (RLB) values are the log-normal random roughnesses calculated from the before tillage height readings, (RLA) the after tillage roughness values, and (RLD) the difference between (RLB) and (RLA). Additional details on the log-normal method of calculating a roughness index are given in reference (1) and in the computer program listed in Appendix E.

The calculation of the maximum absolute difference between the estimated fraction undersize and the observed fraction undersize was included in the log-normal analysis. For over one-half of the plots, the log-normal differences (Appendix A, Figure 42) were larger than the differences found when a normal distribution was used. This evidence supports the conclusion reached previously that a normal distribution could be assumed.

Standard deviation methods

Kuipers (17) used the standard deviation of height readings as a surface roughness index. He estimated the standard deviation of soil height readings from the approximate relationship of the standard deviation to the range for a given sample size. This approximation saved time in manual computations. With a digital computer, approximation methods would not be necessary in calculating the standard deviation.

TREAT-MENT	BLOCK	ROUGHNESS INDEX (INCHES) BEFORE TILLAGE (RLB)	AFTER TILLAGE (RLA)	DIFFERENCE (RLD)
RT	1	0.268	1.137	0.869
	2	0.117	0.612	0.494
	3	0.167	0.683	0.516
	4	0.165	0.694	0.528
	5	0.145	0.719	0.574
	6	0.173	0.801	0.628
PD	1	0.228	0.678	0.450
	2	0.134	0.687	0.553
	3	0.130	0.730	0.600
	4	0.166	0.687	0.520
	5	0.139	0.887	0.747
	6	0.174	0.840	0.666
P	1	0.171	1.008	0.836
	2	0.151	1.316	1.165
	3	0.160	1.107	0.947
	4	0.138	0.919	0.781
	5	0.151	1.050	0.899
	6	0.151	1.017	0.866
PDDH	1	0.172	0.454	0.282
	2	*****	*****	*****
	3	0.144	0.538	0.394
	4	0.147	0.433	0.285
	5	0.161	0.508	0.347
	6	0.156	0.559	0.403
C	1	0.191	0.164	-0.027
	2	0.123	0.156	0.033
	3	0.157	0.139	-0.018
	4	0.144	0.124	-0.020
	5	0.146	0.137	-0.009
	6	0.180	0.174	-0.006

Figure 24. Roughness values calculated using the log-normal method

An index of surface roughness should have the same value for a given soil roughness condition regardless of the field slope. Therefore, before calculating the standard deviation of the height readings, the effects of field slope were removed. Two methods of slope removal were used. One method was correction of each reading for the row effect and column effect as in the log-normal method; the other was removal of linear trends in the heights by multiple regression techniques. The standard deviation of the uncorrected height readings was calculated to serve as a basis for evaluating slope removal methods.

Standard IBM subroutines were utilized in the computer program (Appendix C) for calculating the standard deviation of the uncorrected heights (RS) and the standard error of estimate for the residuals from linear multiple regression (RR). The locations of the height readings along and across the direction of tillage were used as independent variables in the regression. The dependent variable was the height readings. An F test was made of the over-all significance of the regression. Even though the field in which the height readings were taken was relatively level, the regression was highly significant (greater than 0.01) for all plots. This indicated that the linear regression removed some systematic variation from the height readings. It was assumed that the variation removed was due to the presence of a basic field slope upon which random height variations were imposed by tillage operations and not due to a characteristic caused by the tillage operation.

The standard error of estimate of the residuals from linear multiple regression are given in Figure 25. The symbols (RRB), (RRA), and (RRD)

TREAT-MENT	BLOCK	ROUGHNESS INDEX (INCHES) BEFORE TILLAGE (RRB)	AFTER TILLAGE (RRA)	DIFFERENCE (RRD)
RT	1	0.333	1.095	0.762
	2	0.322	0.708	0.386
	3	0.218	0.714	0.496
	4	0.394	0.748	0.354
	5	0.284	0.790	0.506
	6	0.339	0.856	0.517
PD	1	0.295	0.842	0.547
	2	0.258	0.840	0.581
	3	0.189	0.835	0.646
	4	0.219	0.834	0.615
	5	0.261	0.992	0.732
	6	0.308	0.867	0.559
P	1	0.284	1.126	0.842
	2	0.330	1.299	0.970
	3	0.327	1.182	0.856
	4	0.172	0.939	0.768
	5	0.281	1.167	0.885
	6	0.250	1.095	0.845
PDDH	1	0.327	0.568	0.242
	2	*****	*****	*****
	3	0.230	0.899	0.668
	4	0.431	0.577	0.146
	5	0.292	0.682	0.390
	6	0.307	0.691	0.384
C	1	0.328	0.289	-0.039
	2	0.372	0.406	0.034
	3	0.279	0.258	-0.021
	4	0.309	0.284	-0.026
	5	0.349	0.326	-0.023
	6	0.444	0.440	-0.004

Figure 25. Roughness values calculated using standard deviation method, multiple regression residuals

represent values of this roughness index before tillage, after tillage, and the difference between the before and after, respectively. The standard deviations for the uncorrected height readings were also calculated and are given in Figure 26. Values of this roughness index are represented by (RSB), (RSA), and (RSD) for before tillage, after tillage, and the difference.

A roughness index (RC) was calculated as the standard deviation of the height readings following corrections for row and column effects. Each height reading was corrected by subtracting the row and column effects and the over-all average from the original height reading. The corrected height readings were calculated as follows:

$$h'_{ij} = h_{ij} - (\overline{h_{.j}} - \overline{h_{..}}) - (\overline{h_{i.}} - \overline{h_{..}}) - (\overline{h_{..}})$$

where,

h'_{ij} = corrected height readings in the i^{th} row and j^{th} column

$\overline{h_{.j}}$ = average of the original height readings in the j^{th} column

$\overline{h_{i.}}$ = average of the original height readings in the i^{th} row

$\overline{h_{..}}$ = over-all average of the original height readings

The roughness index was then calculated as the standard deviation of the corrected height readings (h'_{ij}). Values of this index are given in Figure 27. The symbols (RCB), (RCA), and (RCD) represent this row and column corrected roughness index before tillage, after tillage, and the difference, respectively.

TREAT-MENT	BLOCK	ROUGHNESS INDEX (INCHES) BEFORE TILLAGE (RSB)	AFTER TILLAGE (RSA)	DIFFERENCE (RSD)
RT	1	0.904	1.357	0.453
	2	0.508	0.991	0.483
	3	0.266	0.781	0.515
	4	0.410	0.770	0.360
	5	0.326	0.791	0.465
	6	0.347	0.924	0.577
PD	1	0.528	0.847	0.319
	2	0.497	0.860	0.363
	3	0.266	1.070	0.804
	4	0.353	0.888	0.535
	5	0.337	1.001	0.664
	6	0.341	0.899	0.558
P	1	0.650	1.140	0.489
	2	0.492	1.329	0.837
	3	0.334	1.188	0.854
	4	0.226	0.957	0.730
	5	0.310	1.195	0.885
	6	0.290	1.106	0.816
PDDH	1	1.045	0.586	-0.459
	2	*****	*****	*****
	3	0.324	1.057	0.734
	4	0.457	0.834	0.377
	5	0.315	0.756	0.441
	6	0.336	0.890	0.554
C	1	0.975	0.942	-0.032
	2	0.539	0.637	0.098
	3	0.315	0.304	-0.011
	4	0.330	0.302	-0.028
	5	0.393	0.383	-0.010
	6	0.479	0.469	-0.010

Figure 26. Roughness values calculated using standard deviation method, uncorrected data

TREAT-MENT	BLOCK	ROUGHNESS INDEX (INCHES) BEFORE TILLAGE (RCB)	AFTER TILLAGE (RCA)	DIFFERENCE (RCD)
RT	1	0.211	0.994	0.783
	2	0.120	0.576	0.456
	3	0.169	0.646	0.477
	4	0.164	0.640	0.476
	5	0.143	0.666	0.523
	6	0.167	0.752	0.584
PD	1	0.206	0.674	0.467
	2	0.121	0.664	0.544
	3	0.129	0.724	0.595
	4	0.158	0.658	0.500
	5	0.129	0.847	0.717
	6	0.165	0.781	0.616
P	1	0.175	0.981	0.806
	2	0.153	1.195	1.042
	3	0.152	1.057	0.905
	4	0.127	0.843	0.716
	5	0.147	1.035	0.888
	6	0.146	0.964	0.818
PDDH	1	0.167	0.489	0.323
	2	*****	*****	*****
	3	0.142	0.530	0.388
	4	0.158	0.406	0.248
	5	0.155	0.511	0.356
	6	0.145	0.561	0.415
C	1	0.196	0.168	-0.028
	2	0.127	0.212	0.085
	3	0.154	0.132	-0.023
	4	0.150	0.121	-0.029
	5	0.140	0.130	-0.009
	6	0.149	0.151	0.001

Figure 27. Roughness values calculated using standard deviation method, data corrected for row and column effects

Comparison of Surface Roughness Indices

Five different roughness indices were calculated from the height data by various procedures as described in the previous sections. These calculations were made to develop a roughness index that would quantitatively describe the soil surface roughness following tillage operations. Each index calculated reflects various aspects of the soil surface. The roughness indices were compared to determine how well they described pertinent surface characteristics. The ease of calculating the indices and the physical significance of the indices was considered. The after tillage roughness indices for the five different calculational procedures are presented in Figure 28.

The RS roughness index was calculated as the standard deviation of uncorrected height readings. This index was easy to calculate, and the known relationship of the standard deviation to the normal distribution helps visualize physical characteristics of the surface measured. The slope of the field has considerable influence on the magnitude of this index. For example, treatment C in block 1 had approximately 4 percent slope, treatment C in block 2 had 1.5 percent slope, and the other blocks of treatment C were approximately level. The RSA roughness value for block 1 was approximately three times larger than the values for blocks 3, 4, and 5 while the value for block 2 was twice the values for 3, 4, 5. This large difference did not occur for the indices that were corrected for plot slope. Where roughness measurements were made on sloping plots, the standard deviation of uncorrected heights was not a suitable index of random roughness.

TREAT-MENT	BLOCK	AFTER TILLAGE ROUGHNESS INDICES (INCHES) RSA	RRA	RCA	RLA	RMA
RT	1	1.357	1.095	0.994	1.137	150.8
	2	0.991	0.708	0.576	0.612	92.3
	3	0.781	0.714	0.646	0.683	94.8
	4	0.770	0.748	0.640	0.694	100.2
	5	0.791	0.790	0.666	0.719	102.0
	6	0.924	0.856	0.752	0.801	113.1
PD	1	0.847	0.842	0.674	0.678	113.7
	2	0.860	0.840	0.664	0.687	114.5
	3	1.070	0.835	0.724	0.730	119.2
	4	0.888	0.834	0.658	0.687	111.6
	5	1.001	0.992	0.847	0.887	144.0
	6	0.899	0.867	0.781	0.840	128.1
P	1	1.140	1.126	0.981	1.008	154.0
	2	1.329	1.299	1.195	1.316	172.4
	3	1.188	1.182	1.057	1.107	154.4
	4	0.957	0.939	0.843	0.919	131.3
	5	1.195	1.167	1.035	1.050	153.8
	6	1.106	1.095	0.964	1.017	147.8
PDDH	1	0.586	0.568	0.489	0.454	100.9
	2	0.913*	0.712*	0.513*	0.506*	99.3*
	3	1.057	0.899	0.530	0.538	118.8
	4	0.834	0.577	0.406	0.433	88.5
	5	0.756	0.682	0.511	0.508	96.2
	6	0.890	0.691	0.561	0.559	100.2
C	1	0.942	0.289	0.168	0.164	17.1
	2	0.637	0.406	0.212	0.156	14.7
	3	0.304	0.258	0.132	0.139	14.2
	4	0.302	0.284	0.121	0.124	14.2
	5	0.383	0.326	0.130	0.137	15.4
	6	0.469	0.440	0.151	0.174	23.0

* ESTIMATED VALUE

Figure 28. After tillage roughness values

The RR roughness index was calculated as the standard error of estimate of the residuals from linear multiple regression. The regression was significant for all plots. This indicated some variation was removed from the height readings. Therefore, the RR roughness values were smaller than the RS values. For sloping plots (for example C-1), this reduction was large; for relatively level plots (for example C-4), the reduction was small. The assumption that the general plot slope could be removed by fitting a plane to the data appeared valid. Since tillage operations did not change the basic field slope, the removal of the variation in height readings caused by slope was desirable. The relationship of the RR index to the actual surface was clear because of knowledge about the standard deviation. Multiple regression analysis added to the computations required, but with a computer this analysis was relatively easy and inexpensive. Because the slope was removed from the RR index, this index was preferable to the RS index.

The final standard deviation roughness index calculated was RC. For this index, the effects of both slope and tillage tool marks were removed by correcting for the row and column effects. This correction removed more variation from the height readings than the multiple regression correction and thus the RC roughness values were smaller than the RR values. The effectiveness of the row and column corrections in removing tillage tool marks was indicated by a larger reduction in roughness values for the plots that had tool marks than for the plots without tool marks. For example, the mean reduction in the RCA values from the RRA values was 40 percent for the plow, disk, disk, and harrow plots which had visible tool marks and only 12 percent for the plowed plots which did not have visible tool marks. By retaining the variation due to tool marks in the roughness index (RR), the total influence of the tillage operations upon the soil surface roughness was measured. The more restrictive RC index measured only the random surface roughness.

The RL roughness index was similar to the RC index except that for RL the height readings were transformed by the natural logarithm and the upper and lower 10 percent of the readings were discarded. Most of the RLA roughness values were larger than the RCA values which indicated that the variance of the height readings was increased by the logarithm transformation. The RC index was considered better than the RL index.

The RM roughness index was calculated as the sum of slopes between selected height readings. This method removed the effect of plot slope but included the influence of tool marks. The roughness values obtained by this method rank the roughness of the plots in approximately the same order as the other roughness indices. The only differences in the rankings were for plots where the roughnesses were nearly equal. This roughness index had two distinct disadvantages. First, the calculations were long and involved several steps. More importantly, the index did not have physical meaning. The index was a sum of a number of different slopes and was meaningless until compared to the value calculated for another surface. The RM index indicated a larger difference between the untilled and tilled treatments than the other indices. The differences among tilled treatments, however, were similar to those for the standard deviation methods.

A final comparison of the roughness indices was made by comparing after tillage treatment means using the multiple range test described by Duncan (8). An analysis of variance was used to calculate the standard error of the treatment means needed for the range test. Values of the roughness indices were not calculated for the PDDH treatment in block 2 because of errors in measuring the height readings for that plot. Estimated values (Figure 28) were calculated to replace the missing values using the formula given by Snedecor (25).

$$X = \frac{aT + bB - S}{(a-1)\ (b-1)}$$

where,

X = missing value

a = number of treatments

b = number of blocks

T = sum of roughness values for PDDH treatments

B = sum of roughness values for block 2

S = sum of all roughness values calculated by a given method

With estimated values for PDDH in block 2, the analysis of variance was calculated for each roughness index with the results given in Figure 29. Because the missing values were estimated, the treatment sums of squares were reduced by a correction for bias (C), where:

$$C = \frac{[B-(a-1)X]^2}{a(a-1)}$$

Estimating the missing value also reduced the degrees of freedom for error from 20 to 19. The treatment sums of squares were partitioned to separate the untilled treatment variation from the variation among the

Source of variation	Sum of squares	Degrees of freedom	Mean square	F
	Analysis for RSA Roughness Index			
Treatments	1.3228	4		
Tilled vs. Check	1.0051	1	1.0051	30.2
Among Tilled	0.3177	3	0.1059	3.2
Blocks	0.1662	5	0.0332	
Error	0.6335	19	0.0333	
	(Standard error of a treatment mean = 0.0746)			
	Analysis for RRA Roughness Index			
Treatments	2.0460	4		
Tilled vs. Check	1.4199	1	1.4199	110.9
Among Tilled	0.6261	3	0.2087	16.3
Blocks	0.0519	5	0.0104	
Error	0.2430	19	0.0128	
	(Standard error of a treatment mean = 0.0462)			
	Analysis for RCA Roughness Index			
Treatments	2.4199	4		
Tilled vs. Check	1.6449	1	1.6449	176.9
Among Tilled	0.7750	3	0.2583	27.8
Blocks	0.0505	5	0.0101	
Error	0.1765	19	0.0093	
	(Standard error of a treatment mean = 0.0394)			
	Analysis for RLA Roughness Index			
Treatments	2.8256	4		
Tilled vs. Check	1.8743	1	1.8743	127.5
Among Tilled	0.9513	3	0.3171	21.6
Blocks	0.0435	5	0.0087	
Error	0.2786	19	0.0147	
	(Standard error of a treatment mean = 0.0494)			
	Analysis for RMA Roughness Index			
Treatments	61665.79	4		
Tilled vs. Check	52347.30	1	52347.30	272.2
Among Tilled	9318.49	3	3106.16	16.2
Blocks	921.01	5	184.20	
Error	3653.32	19	192.28	
	(Standard error of a treatment mean = 5.659)			

Figure 29. Analyses of variance of the roughness indices

tilled treatments. Except for the RSA index, the variation among treatments was significant at the 1 percent significance level. The standard errors of the treatment means (Figure 29) were calculated as

$$\text{Standard error of a treatment mean} = \sqrt{\frac{\text{error mean square}}{\text{number of blocks}}} .$$

These standard errors were multiplied by the critical values for the range test as given by Harter (9) to obtain the shortest significant ranges of the treatment means.

The results of the range test at the 1 percent significance level are given in Figure 30. Any two treatment means that are not underscored by the same line were significantly different. These results verified the earlier observations concerning the different indices. The absence of significant differences among the means of the tillage treatments for the RSA index supported the observation that the slope should be removed. The significant differences among the means for the other indices were the same except that the PDDH mean was significantly different from the PD and RT means for the indices where the tool mark effect was removed (RCA and RLA). As can be seen in Figures 31-34, and Figure 37, PDDH was the only treatment which had visible tool marks. The correction for tool marks reduced the variation causing the PDDH treatment mean to be significantly smaller than the PD and RT means. On the other hand, when the variation due to tool marks was not removed, the PDDH mean was not significantly different from the PD and RT means.

For RSA Roughness Index

Number of Means:		2	3	4	5
Shortest Sign. Range (1%):		0.302	0.315	0.323	0.329
Treatment:	C	PDDH	PD	RT	P
Treatment Mean	0.506	0.839	0.928	0.936	1.152

For RRA Roughness Index

Number of Means:		2	3	4	5
Shortest Sign. Range (1%):		0.187	0.195	0.200	0.204
Treatment:	C	PDDH	RT	PD	P
Treatment Mean:	0.334	0.688	0.819	0.868	1.135

For RCA Roughness Index

Number of Means:		2	3	4	5
Shortest Sign. Range (1%):		0.159	0.166	0.171	0.174
Treatment:	C	PDDH	RT	PD	P
Treatment Mean:	0.152	0.502	0.712	0.725	1.013

For RLA Roughness Index

Number of Means:		2	3	4	5
Shortest Sign. Range (1%)		0.200	0.209	0.214	0.218
Treatment:	C	PDDH	PD	RT	P
Treatment Mean:	0.149	0.500	0.751	0.774	1.070

For RMA Roughness Index

Number of Means:		2	3	4	5
Shortest Sign. Range (1%):		22.9	23.9	24.5	25.0
Treatment:	C	PDDH	RT	PD	P
Treatment Mean:	16.4	100.6	108.9	121.8	152.3

Figure 30. Multiple range test of differences among treatment means

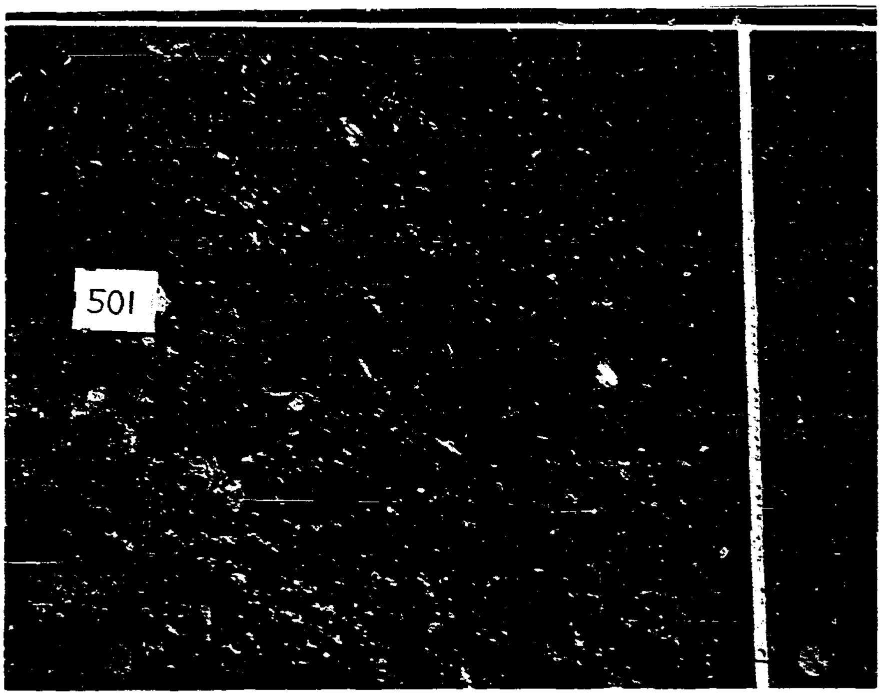


Figure 31. Typical power rotary tilled surface

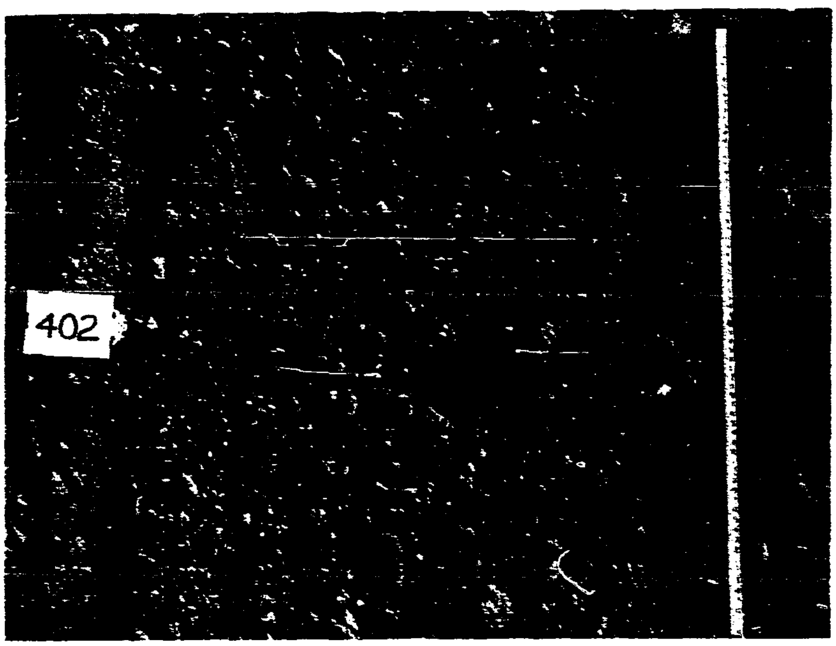


Figure 32. Typical plowed and disked surface

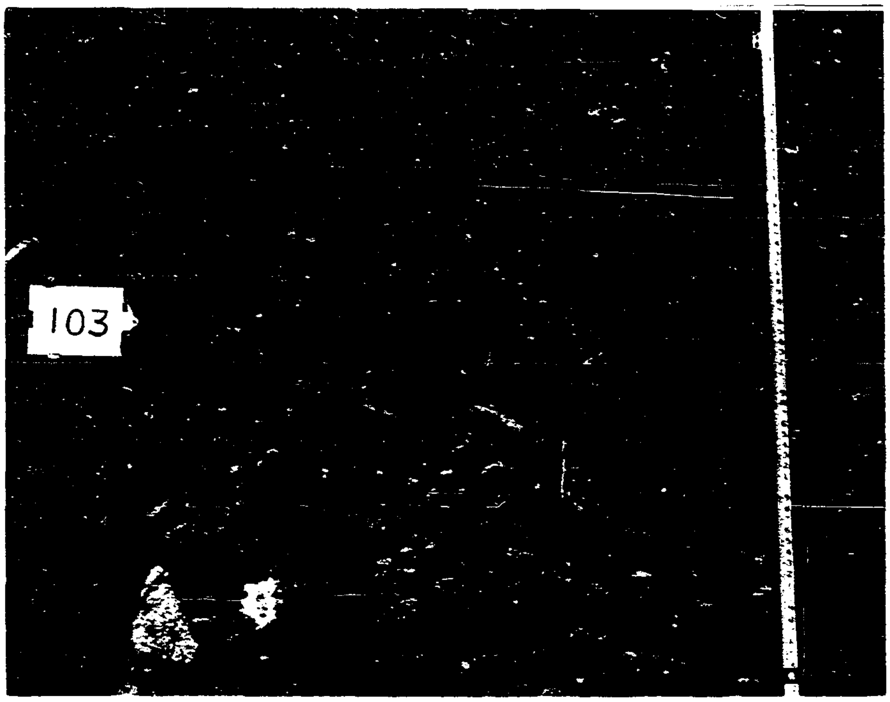


Figure 33. Typical plowed surface

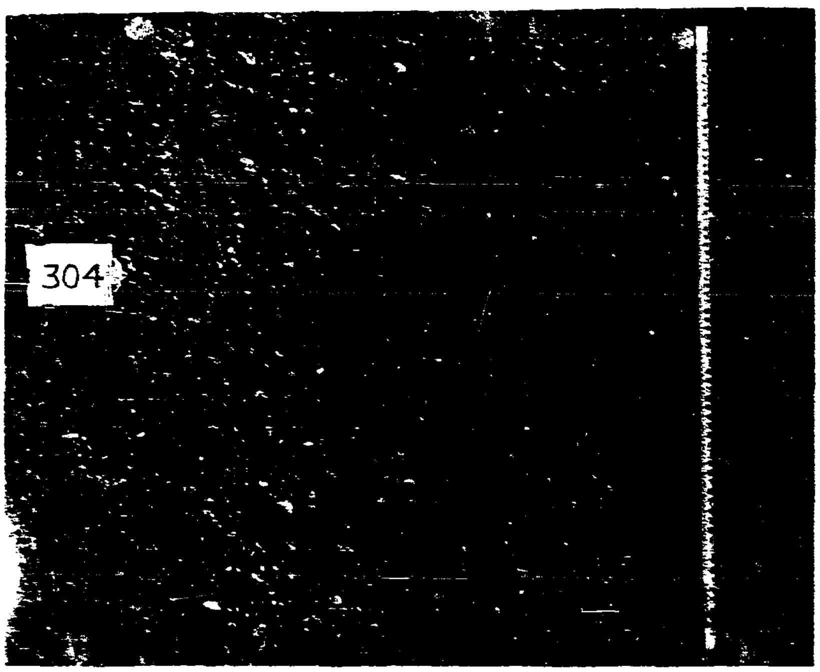


Figure 34. Typical plowed, disked, disked, and harrowed surface

Number of Height Readings Required

Considerable time and expense were required to record and analyze 4800 height readings per plot. So the cost of future studies could be reduced, the minimum number of readings necessary to adequately estimate the RR roughness index was determined.

The values of the RRA roughness index (standard deviation of the residuals from regression), calculated using the 1x1-inch data spacing, were assumed to be the correct (population) values. By using only part of the height readings to calculate the RRA index, various data spacings were simulated. The roughness values obtained from the calculations with simulated spacings were used as estimates of the population values. Confidence intervals were calculated for the estimated values to determine how well the roughness values calculated from the various simulated spacings approximated the 1x1-inch spacing values.

For equally spaced height readings, no information could be obtained about frequencies above the Nyquist frequency (4) which is given by:

$$f_N = \frac{1}{2\Delta d}$$

where,

f_N = Nyquist frequency (cycles/inch)

Δd = distance between readings (inches).

Frequencies which were higher than the Nyquist frequency were indistinguishable from the Nyquist frequency for equally spaced data. For the 1-inch data spacing used in this study, information about frequencies above 0.5 cycle per inch was indistinguishable. Thus, the periodic nature of any surface configurations, such as tillage tool marks, which were spaced closer than 2 inches could not be distinguished from a 2-inch period. Since the periodic surface configurations expected on a tilled soil surface would have a period larger than 2 inches, the 1-inch data spacing was acceptable. If 2-inch data spacings were used, surface characteristics with a period of 4 inches or less would be confounded. Since some tools (for example, surface packers) produce tool marks which are spaced 4 inches or less, a 2-inch spacing of height readings across the direction of tillage would be unacceptable. Therefore, any reduction in the number of height readings used should only be obtained by increasing the spacing in the direction of tillage.

Estimated roughness values were calculated using simulated data spacings of 1x4, 1x5, ..., 1x9 inches. The height readings used for the simulated data spacings were centered as closely as possible over the total measured area. For example, for the 1x5 spacing, the 3rd, 8th, ..., 78th columns of data were used. The original height readings were used in the calculations to fit a new multiple regression plane through the data of the simulated data spacing. The residuals from this new plane were used to calculate the estimated RRA roughness values.

Confidence intervals were calculated for each of the estimated roughness values. The confidence interval for the variance of a normal population (21) was used. The square roots of the limits were obtained to estimate the confidence interval for the standard deviation or RRA roughness index. The upper limit of the 95-percent confidence interval was calculated as follows:

$$U = \sqrt{\frac{\Sigma h^2}{\chi^2_{0.025}}}$$

where,

U = upper limit

h = height residuals for simulated data spacing

$\chi^2_{0.025}$ = estimated chi-square

The lower limit (L) was calculated as

$$L = \sqrt{\frac{\Sigma h^2}{\chi^2_{0.975}}}$$

Since the degrees of freedom for the estimated roughness values were large (greater than 500), the chi-square probabilities were estimated from the standard normal distribution. Using the mean and variance (degrees of freedom and twice the degrees of freedom, respectively) for the chi-square distribution, estimates of the chi-square percentage points were calculated as,

$$\chi^2_{\gamma,\nu} = \sqrt{2\nu}\, Z_\gamma + \nu$$

where,

χ^2 = estimated chi-square

γ = probability of a larger value by chance

ν = degrees of freedom

Z = cumulative normal distribution.

The 95-percent confidence intervals for the estimated roughness values calculated using simulated data spacings of 1x4 and 1x5 included the population value for all plots. The intervals for the 1x6 (Figure 35) and the 1x7-inch data spacing included the population value for all but one plot. For the 1x8-inch spacing (Figure 36), 6 of the confidence intervals did not include the population value. Statistically, one exception out of 20 plots could be expected by chance. Therefore, from the simulated data spacings, one would not expect to estimate the 1x1-inch data spacing roughness values with data spacings greater than 1x7 inches. Since the estimated values were calculated from population heights instead of heights actually measured at the different locations, there were no reading errors in the comparison of the data spacings. To account, at least partially, for the larger error that would exist for different readings, the 1x6-inch data spacing was chosen over the 1x7-inch spacing.

Power Spectral Density Analysis

In addition to random surface roughness, tillage operations cause forced configuations of the soil surface. Most unpowered tillage implements leave oriented tool marks on the soil surface under some soil conditions. These tool marks usually occur at fixed, equally spaced intervals across the direction of tillage. None of the calculated random roughness indices (RR, RC, etc.) characterized the configurations caused by tillage tools. The RR index included the variation in height readings due to tool marks but did not characterize the tool marks.

Power spectral density analysis, a technique used to study the

TREAT-MENT	BLOCK	LOWER LIMIT	RRA (1X6)	UPPER LIMIT
RT	1	1.057	1.109	1.168
	2	0.643	0.674	0.711
	3	0.695	0.729	0.768
	4	0.704	0.738	0.778
	5	0.718	0.753	0.793
	6	0.788	0.826	0.870
PD	1	0.809	0.848	0.894
	2	0.829	0.869	0.916
	3	0.789	0.828	0.872
	4	0.812	0.852	0.897
	5	0.973	1.021	1.076
	6	0.836	0.876	0.923
P	1	1.073	1.125	1.185
	2	1.193	1.251	1.318
	3	1.142	1.198	1.262
	4	0.887	0.930	0.980
	5	1.090	1.143	1.204
	6	1.075	1.127	1.187
PDDH	1	0.545	0.571	0.602
	2	*****	*****	*****
	3	0.854	0.896	0.944
	4	0.532	0.557	0.587
	5	0.650	0.682	0.719
	6	0.652	0.684	0.720
C	1	0.274	0.287	0.303
	2	0.383	0.402	0.424
	3	0.227	0.238	0.250
	4	0.265	0.278	0.293
	5	0.307	0.322	0.339
	6	0.423	0.444	0.468

Figure 35. RRA roughness values and 95-percent confidence intervals for simulated 1x6-inch data spacing

TREAT- MENT	BLOCK	LOWER LIMIT	RRA (1X8)	UPPER LIMIT
RT	1	1.026	1.083	1.150
	2	0.670	0.707	0.751
	3	0.732	0.772	0.820
	4	0.657	0.693	0.736
	5	0.724	0.764	0.812
	6	0.792	0.836	0.888
PD	1	0.800	0.844	0.897
	2	0.794	0.838	0.890
	3	0.781	0.824	0.875
	4	0.792	0.835	0.887
	5	0.933	0.985	1.046
	6	0.886	0.935	0.992
P	1	1.029	1.086	1.154
	2	1.205	1.272	1.351
	3	1.119	1.181	1.254
	4	0.897	0.946	1.005
	5	1.102	1.163	1.235
	6	0.974	1.028	1.092
PDDH	1	0.539	0.568	0.604
	2	*****	*****	*****
	3	0.830	0.876	0.930
	4	0.552	0.583	0.619
	5	0.647	0.682	0.725
	6	0.638	0.674	0.715
C	1	0.270	0.285	0.303
	2	0.385	0.407	0.432
	3	0.225	0.237	0.252
	4	0.266	0.281	0.298
	5	0.286	0.302	0.321
	6	0.407	0.429	0.456

Figure 36. RRA roughness values and 95-percent confidence intervals for simulated 1x8-inch data spacing

periodic aspects of several types of surfaces, was used to describe tillage tool marks.

The columns of height readings were equally spaced measurements of the continuous soil surface across the direction of tillage. If the tillage operation left tool marks, they influenced the way the height readings fluctuated within a column. By considering the height measurements a function of location, the relationship between adjacent height readings was determined.

For a function of time or space X(t), the covariances between values of X(t) at different times or locations are required to completely statistically describe the function (14). If the function is stationary, i.e., the statistical properties are unaffected by translations of the origin for time or location, the covariances depend only on the time or location separation. There are (n-1) covariances necessary to describe a stationary function. These covariances, called autocovariances, are given by:

$$R(k) = E\,[X(t)\;X(t+k)]$$

where

R(k) = autocovariance at lag (time or location separation) k

E = expected value

X(r) = stationary function of time or location.

Since tillage tool marks are generally equally spaced across a tilled field and the random roughness is approximately Gaussian, the soil surface across the direction of tillage was assumed to be a stationary, random function. With these assumptions, the power spectral density analysis was used to characterize the periodic aspects of the soil surface.

The periodogram function described by Jenkins (14) was used to investigate the periodic nature of the soil surface. The profilometer frame was located over the plots so that height readings were measured perpendicular and parallel to the direction of tillage. Any tillage tool marks were reflected in the columns of height readings measured across the direction of tillage (60 readings on 1-inch centers).

Periodogram estimates were calculated for each column of height readings in the following manner. First, the sample autocovariances were calculated as

$$c_k = \frac{1}{n} \sum_{t=1}^{n-k} h_t h_{t+k}$$

where

c_k = sample autocovariance,

h_t, h_{t+k} = height readings,

n = number of height readings in a column (60) and

k = lag (0, 1, 2, 3, ..., 59).

Using these sample autocovariances, the periodogram estimates were calculated as follows:

$$I_n\ (\theta_j) = \frac{1}{\pi} \left[c_o + 2 \sum_{k=1}^{n-1} c_k \cos \theta_j\ k \right]$$

where

$I_n\ (\theta_j)$ = periodogram estimate at frequency θ_j,

c_o = sample variance,

c_k = sample autocovariance,

θ_j = frequency ($2\,\pi j/n$),

n = number of height readings and

k = lag.

Smoothed graphs of the periodogram function were obtained by averaging the periodogram estimates calculated for each column of readings within a plot. These average values were plotted versus the frequency θ_j (Appendix B, Figure 43) to show the variance decomposition with frequency.

The graphs of the periodogram function show how the variance for a plot was related to periodic surface configurations. The area under the periodogram graph equals n/π times the variance. Spikes in the graph indicate a significant contribution to the total variance by periodic surface irregularities, e.g., tillage tool marks. The spikes occur at or near the frequencies of the periodic surface configurations.

The periodogram graphs (Figure 43) for blocks 3, 4, 5 and 6 of PDDH have spikes at or near 0.117 cycles/inch. At this frequency there would be approximately seven cycles across the 60-inch plot width. Since the spike-tooth harrow left seven visible tool marks across these plots (Figure 34), the periodogram determination agrees with visual observation. Block 1 of this treatment was not ridged and block 2 data were missing.

For block 1 of P, the periodogram shows a spike at 0.083 cycles/inch. The period for this frequency (approximately 12 inches) is close to the width of the 14-inch moldboard plow bottom. Therefore, this periodic variation was reasonable even though visually it could not be seen (Figure 33). For all other plots, there was little or no evidence of periodic variation from either the periodograms or visual inspection.

The readings for the simulated 1x6-inch spacing were also used to calculate periodogram estimates. These estimates were superimposed on the 1x1-inch periodogram graphs. Inspection of these graphs indicated that periodograms for the 1x6-inch spacing were very similar to the 1x1-inch periodograms and the same surfaces were indicated as being periodic.

SUMMARY AND CONCLUSIONS

The random roughness of tilled soil surfaces was described quantitatively by various roughness indices. The standard deviation of slope corrected surface height readings was satisfactory for describing the amplitudes of surface variations. The RR index described the amplitude variations of the height residuals from the plane of best fit through the data. The plane fitting removed uniform variation that was present because of field slope. The RC index gave the height variation of the surface after both slope and tillage tool marks had been removed. Both indices were adequate descriptions of the soil surface.

The choice of which random roughness index to use must be based on the proposed use of the index. To study the correlation between surface roughness and most surface related properties, the RR index would be preferred. The presence of tillage tool marks could greatly affect erosion, surface water storage, infiltration, machine performance, etc. Thus, for these studies, the effect of tool marks should be included in the random roughness index. The effect of tool marks should probably be removed from the roughness index if properties such as clod size or clod size distribution are to be correlated with roughness.

Power spectral density analysis was used to find the frequency of periodic surface irregularities. With this technique, the roughness caused by tool marks was distinguished from random roughness. Averages of the periodogram estimates for individual columns of heights gave smooth curves of the variance decomposition with frequency. The combination of the spectral density analysis with the RRA roughness index provides a description of both the random surface roughness and the periodic variation of the surface. Visible tillage tool marks were clearly determined by the spectral density analysis.

The differences in the roughness values for a given treatment were larger between some blocks than expected. The roughness value for block 1 of the rotary tillage plot, for example, was much higher than the roughness of the other rotary tilled plots. Comparison of Figures 31, 33 and 38 show that the roughness values were consistent with the appearance of the plots.

The collection and analysis of surface roughness data provided the following information:

1. The standard deviation of slope corrected height readings effectively described random surface roughness.
2. The periodogram function provided information about the periodic variations of the soil surface.
3. Linear multiple regression removed variation due to field slope from the random roughness index.
4. Acceptable random roughness values were determined from height readings measured on 1-inch centers across the direction of tillage and 6-inch centers in the direction of tillage.
5. Smooth estimates of the periodogram function were obtained from the 1x6-inch data spacing.
6. Soil surface height readings were approximately normally distributed.
7. The automatic recording profilometer provided a fast, accurate means of measuring height readings.

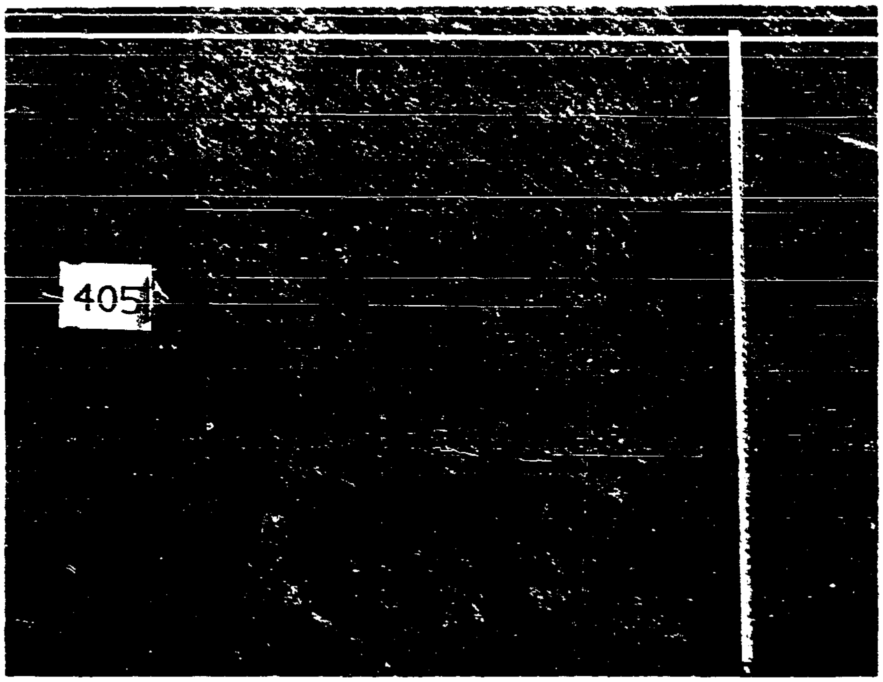


Figure 37. Typical untilled surface

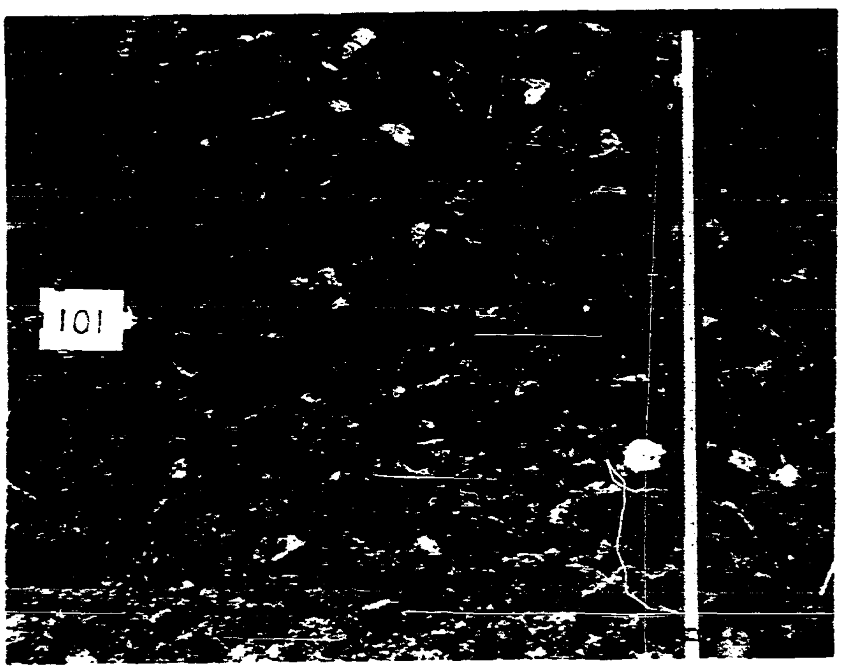


Figure 38. Rough power rotary tilled surface

SUGGESTIONS FOR FUTURE STUDIES

The RR roughness index and periodogram graphs provided sensitive measures of soil surface roughness. Using these measurements, correlations of the surface condition to other soil properties should be investigated. Soil moisture and temperature changes should be monitored for various tillage and cropping systems and compared to the surface roughness. The relationship of surface roughness to pesticide application, weed control, crop emergence and seedbed condition should also be studied. The influence of roughness on surface water storage, infiltration and runoff could provide valuable erosion control information.

Pertinent soil properties that can be correlated to surface roughness could be investigated by obtaining profilometer measurement of the soil surface. Establishing the relationship of soil roughness to other soil properties should make it possible to clearly define performance specifications for tillage operations. Ideal surface conditions could be defined and tillage tool design as well as performance specifications could be directed toward producing those conditions.

The roughest plots for this study were smoother than would occur for many soil conditions. The adequacy of the 1x6-inch data spacing should be verified over a wider range of roughness. The effect of reading error variation should be included in future spacing studies.

REFERENCES

1. Allmaras, R. R., Burwell, R. E., Larson, W. E., and Holt, R. F. Total porosity and random roughness of the interrow zone as influenced by tillage. U.S. Department of Agriculture Agricultural Research Service Conservation Research Report No. 7. 1966.

2. Baver, L. D. Soil physics. 3rd ed. New York, New York, John Wiley and Sons. 1956.

3. Bickel, E. Roughness standards today. Microtecnic 12:41-50. 1958.

4. Blackman, R. B. and Tukey, J. W. The measurement of power spectra. New York, New York, Dover Publications, Inc. 1958.

5. Buchele, Wesley F. A power sampler of undisturbed soils. American Society of Agricultural Engineers Transactions 4:185-187, 191. 1961.

6. Burwell, R. E., Allmaras, R. R., and Amemiya, M. A field measurement of total porosity and surface microrelief of soils. Soil Science Society of America Proceedings 27:697-700. 1963.

7. Darlington, J. R. and Milliman, P. A progress report on the evaluation and application study of the General Motors rapid travel road profilometer. Highway Research Record No. 214: 50-67. 1968.

8. Duncan, David B. Multiple range and multiple F tests. Biometrics 11:1-42. 1955.

9. Harter, H. Leon. Critical values for Duncan's new multiple range test. Biometrics 16:671-685. 1960.

10. Hasunuma, Hirosi. Statistical characteristic of surface profile. Japan Society of Precision Engineering Bulletin 1:205-211. 1965.

11. Heermann, Dale F. Hydraulics of small open channels. Unpublished Masters thesis. Fort Collins, Colorado, Library, Colorado State University. 1964.

12. Houbolt, John C. Runway roughness studies in the aeronautical field. American Society of Civil Engineers Proceedings Air Transport Division AT 1. 1961.

13. Hveem, F. N. Devices for recording and evaluating pavement roughness. Highway Research Board Bulletin 264:1-26. 1960.

14. Jenkins, G. M. General considerations in the analysis of spectra. Technometrics 3:133-166. 1961.

15. Jenkins, Gwilym M. and Watts, Donald G. Spectral analysis and its applications. San Francisco, California, Holden-Day, Inc. 1968.

16. Kubo, Moritada. Instruments for statistical analysis of surface roughness. Japan Society of Precision Engineering Bulletin 1: 255-262. 1965.

17. Kuipers, H. A reliefmeter for soil cultivation studies. Netherlands Journal of Agricultural Science 5:255-262. 1957.

18. Kuipers, H. and VanOuwerkerk, C. Total pore-space estimations in freshly ploughed soil. Netherlands Journal of Agricultural Science 11:45-53. 1963.

19. Luttrell, Dan Houston. The effect of tillage operations on bulk density and other physical properties of the soil. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1963.

20. Merva, George E., Brazee, R. D., and Schwab, Glenn O. Theoretical considerations of watershed surface description. American Society of Agricultural Engineers Paper No. 68-714. 1968.

21. Ostle, Bernard. Statistics in research. 2nd ed. Ames, Iowa, Iowa State University Press. 1963.

22. Quinn, B. E. and Hagen, K. Problems encountered in using elevation power spectra as criteria of pavement condition. Highway Research Record No. 189:166-181. 1967.

23. Schafer, Robert L. and Lovely, Walter G. A recording soil surface profile meter. Agricultural Engineering 48:280-282. 1967.

24. Shaw, R. H., Nielsen, D. R., and Runkles, J. R. Evaluation of some soil moisture characteristics of Iowa soils. Iowa Agricultural and Home Economics Experiment Station Research Bulletin 465. 1959.

25. Snedecor, George W. Statistical methods. 5th ed. Ames, Iowa, Iowa State University Press. 1956.

26. Stone, Richard O. and Dugundji, James. A study of microrelief: Its mapping, classification, and quantification by means of a fourier analysis. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi Contract Report 3-82. 1963.

27. VanDeusen, B. D. A study of the vehicle ride dynamics aspect of ground mobility. I. Summary. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi Contract Report 3-114. 1965.

28. VanDeusen, B. D. and Hoppe, C. H. A study of the vehicle ride dynamics aspect of ground mobility. IV. Field measurements. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi Contract Report 3-114. 1965.

29. Wilton, B. Effect of cultivations on the level of the surface of a soil. Journal of Agricultural Engineering Research 9:214-219. 1964.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to:

Dr. C. W. Bockhop, major professor, and Mr. W. G. Lovely for their suggestions and guidance in this research and thesis preparation.

Doctors W. A. Fuller, T. E. Hazen, S. J. Marley and D. F. Young for their assistance as committee members.

The United States Department of Agriculture and the Agricultural Engineering Department for providing facilities and financing this research.

Mr. J. F. Andrew and Mr. M. T. Krezinski for assistance in constructing the profilometer and collecting field data.

Mrs. Violet Johnson and Mrs. Kay Mikkelsen for typing and editing assistance.

My wife, Joyce, and children, Dana, Shelly, and Kevin for their continued encouragement and patience during this study.

APPENDIX A: RESULTS OF DISTRIBUTION ANALYSES

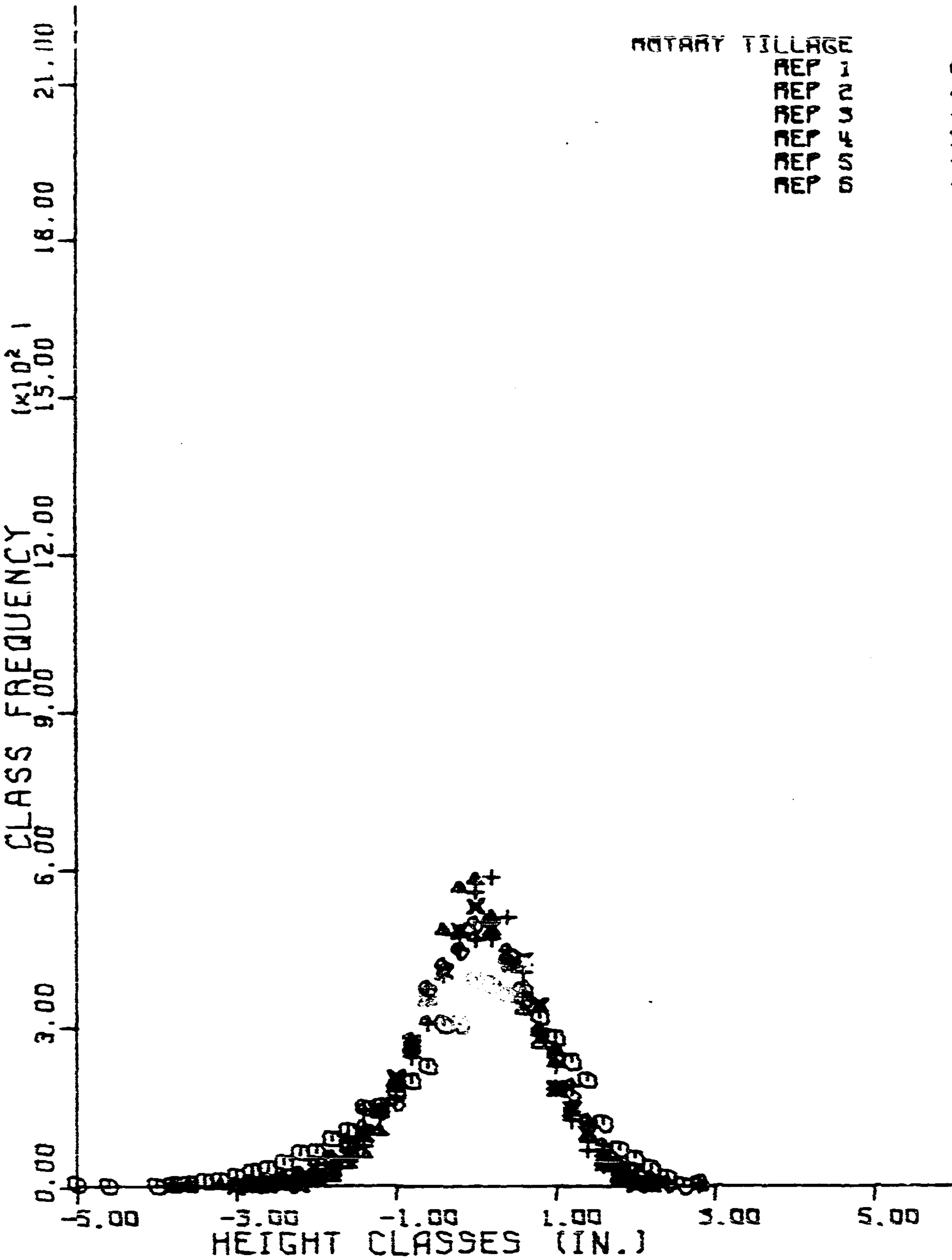


Figure 39. Histograms of residuals from multiple regression

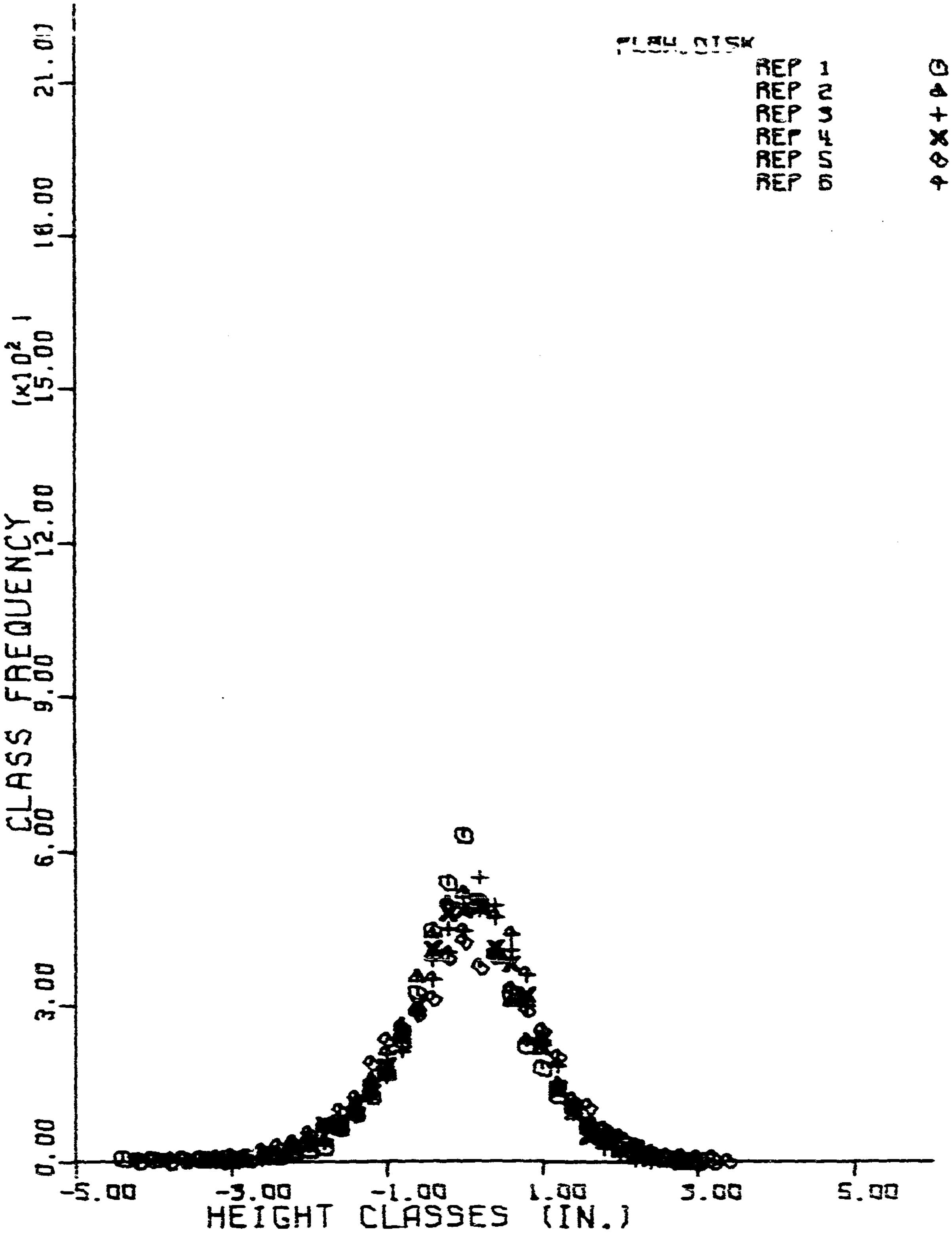


Figure 39. (continued)

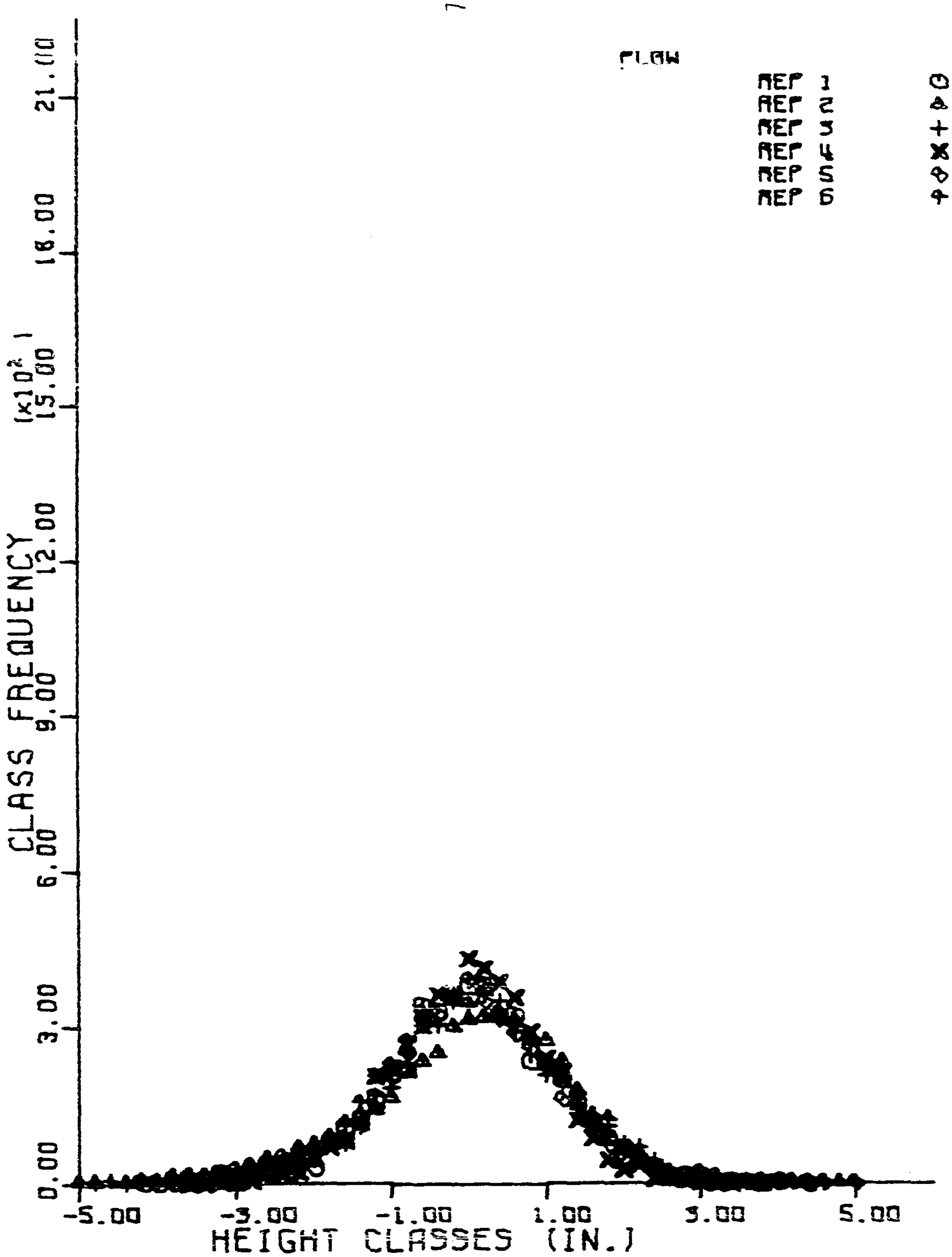


Figure 39. (continued)

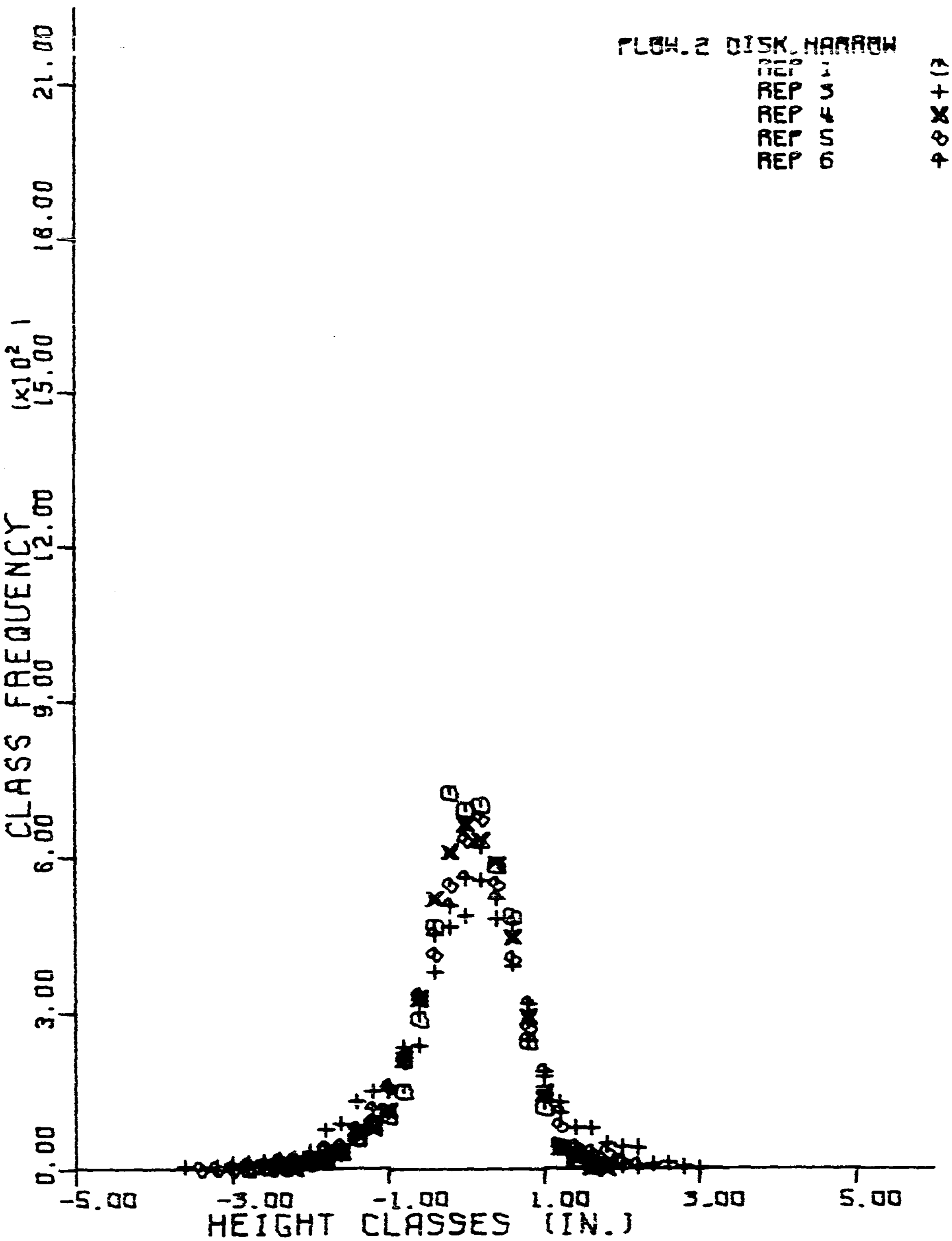


Figure 39. (continued)

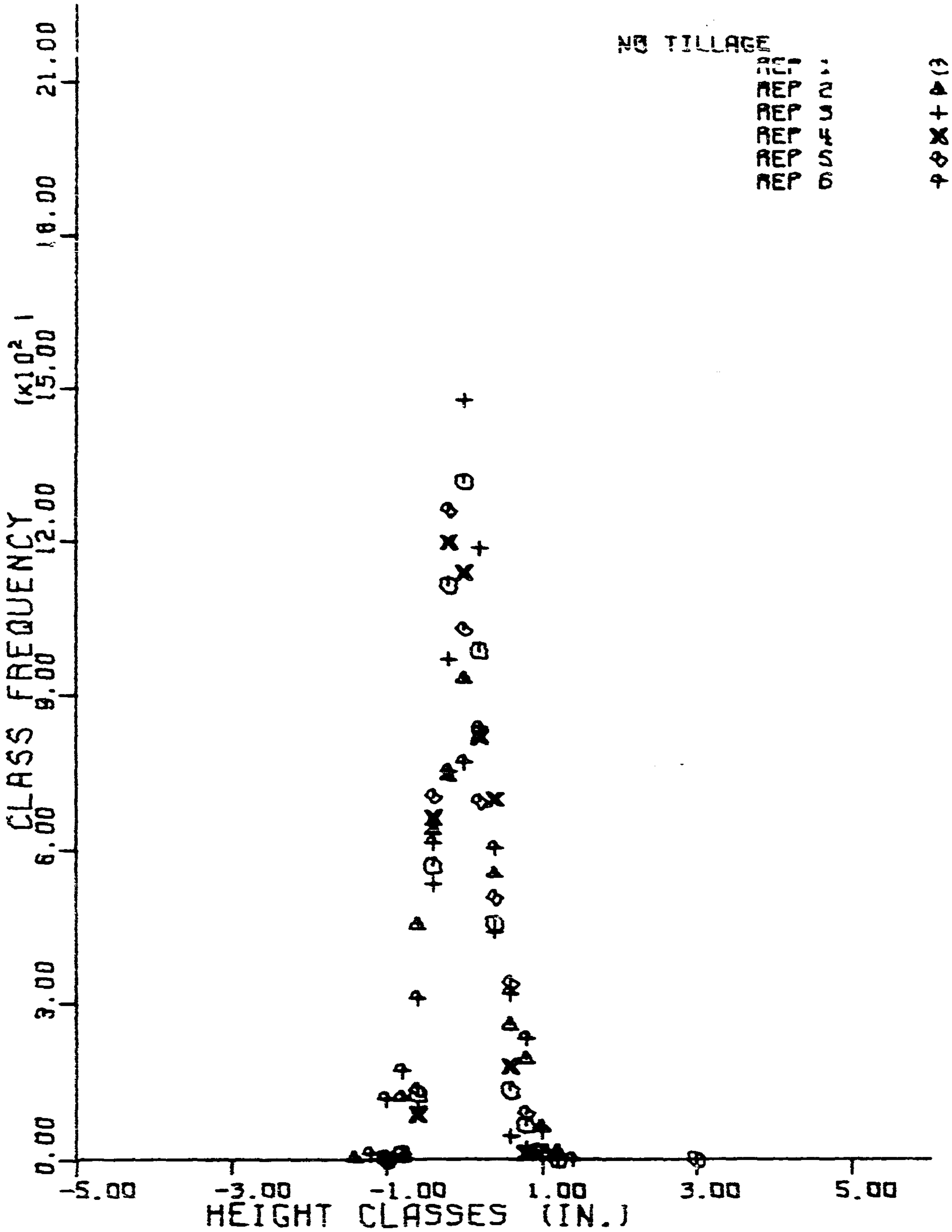


Figure 39. (continued)

TREAT- MENT	BLOCK	5 LARGEST ABSOLUTE DIFFERENCES (PERCENT)				
RT	1	1.6	1.5	1.5	1.1	1.1
	2	1.2	0.9	0.9	0.8	0.6
	3	1.5	1.1	0.8	0.7	0.7
	4	1.2	1.1	0.8	0.5	0.5
	5	1.3	0.7	0.5	0.5	0.4
	6	0.9	0.9	0.9	0.8	0.8
PD	1	3.7	2.0	1.4	1.2	1.2
	2	1.3	1.2	1.2	1.2	1.1
	3	2.1	1.8	1.6	1.3	1.2
	4	1.1	1.0	1.0	0.9	0.7
	5	0.9	0.9	0.9	0.8	0.5
	6	1.9	1.6	1.5	1.3	1.2
P	1	1.0	1.0	0.9	0.8	0.8
	2	1.2	1.1	1.0	1.0	0.9
	3	1.1	1.1	1.0	0.9	0.9
	4	0.7	0.6	0.6	0.5	0.5
	5	1.3	0.9	0.9	0.9	0.8
	6	0.7	0.5	0.4	0.4	0.3
PDDH	1	2.2	2.1	2.0	1.9	1.4
	2	****	****	****	****	****
	3	2.9	2.2	2.0	1.5	1.3
	4	1.3	1.2	1.2	0.9	0.8
	5	2.9	1.6	1.5	1.5	1.2
	6	1.9	1.9	1.5	1.2	1.1
C	1	1.8	1.3	1.1	1.0	0.8
	2	2.8	1.8	1.3	1.2	1.2
	3	2.5	2.1	1.5	1.4	0.5
	4	4.6	4.0	3.8	3.3	3.2
	5	6.2	5.6	3.1	2.7	2.5
	6	1.9	1.3	1.2	1.0	0.8

Figure 40. Differences between experimental and theoretical class frequencies for histograms of residuals from regression

TREAT-MENT	BLOCK	5 LARGEST ABSOLUTE DIFFERENCES (PERCENT)				
RT	1	1.2	1.0	0.9	0.9	0.9
	2	1.9	1.3	1.2	0.9	0.8
	3	1.1	1.0	0.8	0.6	0.5
	4	1.4	1.2	0.8	0.8	0.7
	5	1.2	0.7	0.5	0.4	0.4
	6	1.2	0.8	0.7	0.6	0.4
PD	1	4.1	3.3	1.9	1.5	1.4
	2	1.6	1.4	0.9	0.7	0.7
	3	1.1	1.1	1.0	1.0	1.0
	4	1.3	1.1	1.0	1.0	1.0
	5	0.9	0.9	0.8	0.8	0.7
	6	1.7	1.6	1.5	1.5	1.1
P	1	0.8	0.8	0.8	0.7	0.6
	2	1.3	0.9	0.9	0.7	0.6
	3	1.3	1.2	1.1	1.0	0.9
	4	0.8	0.6	0.6	0.6	0.5
	5	1.7	1.0	0.9	0.8	0.7
	6	0.7	0.7	0.6	0.5	0.4
PDDH	1	3.4	2.7	2.1	1.7	1.6
	2	****	****	****	****	****
	3	13.2	7.0	6.3	5.6	5.2
	4	1.7	1.6	1.4	1.3	1.2
	5	1.7	1.6	1.1	0.9	0.9
	6	2.5	2.0	1.2	1.2	1.2
C	1	5.0	4.9	4.1	4.1	3.7
	2	6.1	5.9	4.7	4.1	2.8
	3	2.8	2.2	1.7	1.5	0.9
	4	6.1	4.3	4.0	1.9	1.8
	5	5.9	4.1	2.0	1.0	0.9
	6	2.4	2.2	1.8	1.3	1.1

Figure 41. Differences between experimental and theoretical class frequencies for histograms of uncorrected data

TREAT-MENT	BLOCK	MAXIMUM DIFFERENCES (PERCENT) REGRESSION	MEAN	LOG-NORMAL
RT	1	5.2	4.4	4.5
	2	1.5	3.4	2.6
	3	2.7	1.8	3.8
	4	1.6	2.9	3.5
	5	1.5	1.9	3.7
	6	2.6	3.0	3.3
PU	1	4.3	4.9	4.5
	2	2.7	2.8	3.7
	3	4.6	3.0	3.9
	4	2.7	3.6	4.9
	5	2.3	2.8	4.0
	6	4.7	4.6	4.0
P	1	3.0	2.6	3.9
	2	4.3	3.2	5.0
	3	3.1	3.7	4.5
	4	1.7	2.1	4.7
	5	3.0	3.0	2.1
	6	0.8	1.4	2.3
PUDH	1	4.8	6.0	4.5
	2	****	****	****
	3	4.9	15.2	4.5
	4	2.5	3.7	4.8
	5	4.4	3.0	5.4
	6	3.7	3.3	6.3
C	1	2.2	11.7	1.0
	2	2.6	11.3	3.1
	3	2.2	5.5	1.4
	4	4.7	7.5	0.7
	5	6.9	5.3	1.3
	6	2.0	4.1	1.1

Figure 42. Maximum percentage differences between experimental and theoretical cumulative distribution functions for regression corrected, mean corrected, and log-normal data

APPENDIX B: GRAPHS OF PERIODOGRAM FUNCTION

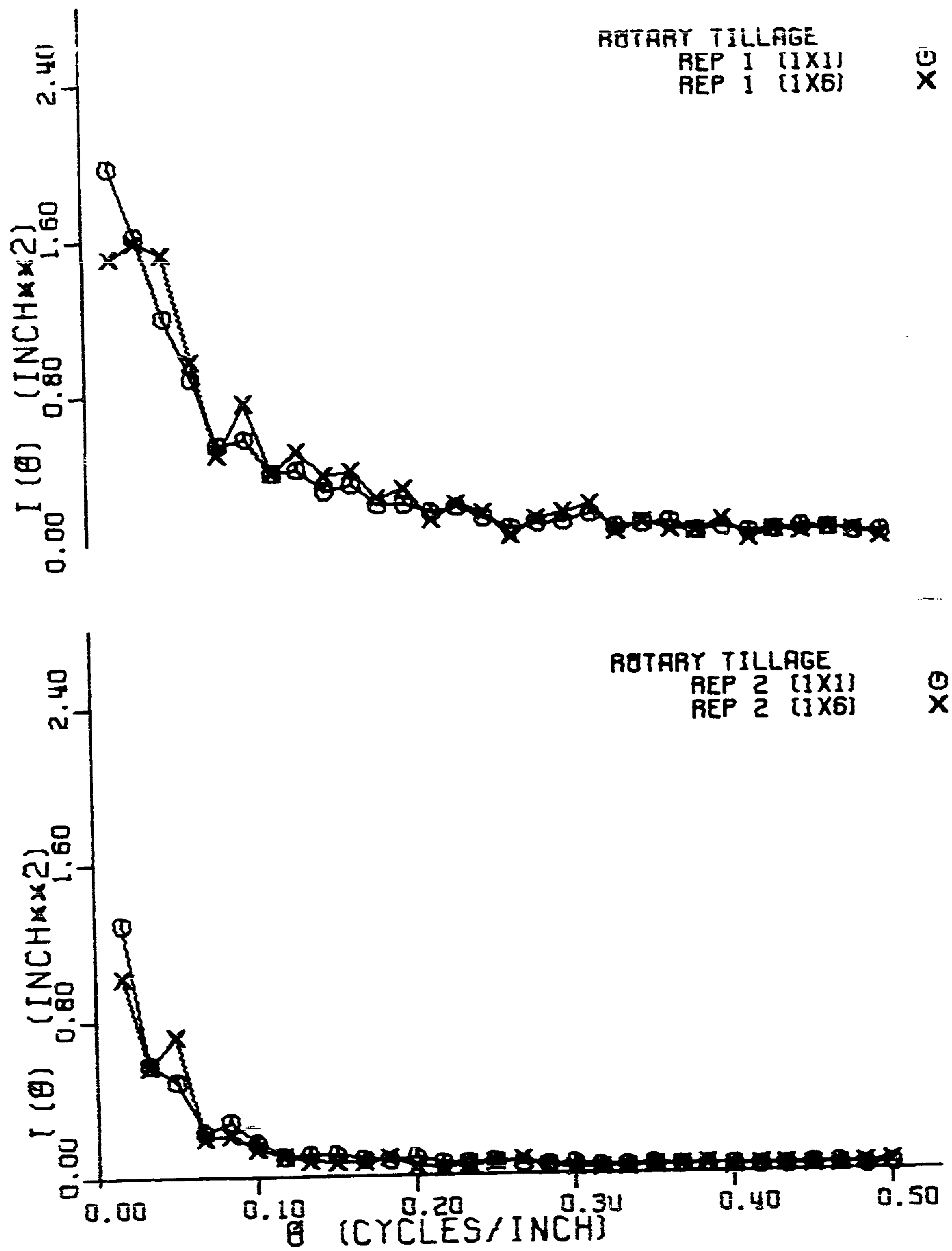


Figure 43. Periodogram graphs, 1x1-inch and simulated 1x6-inch data spacings

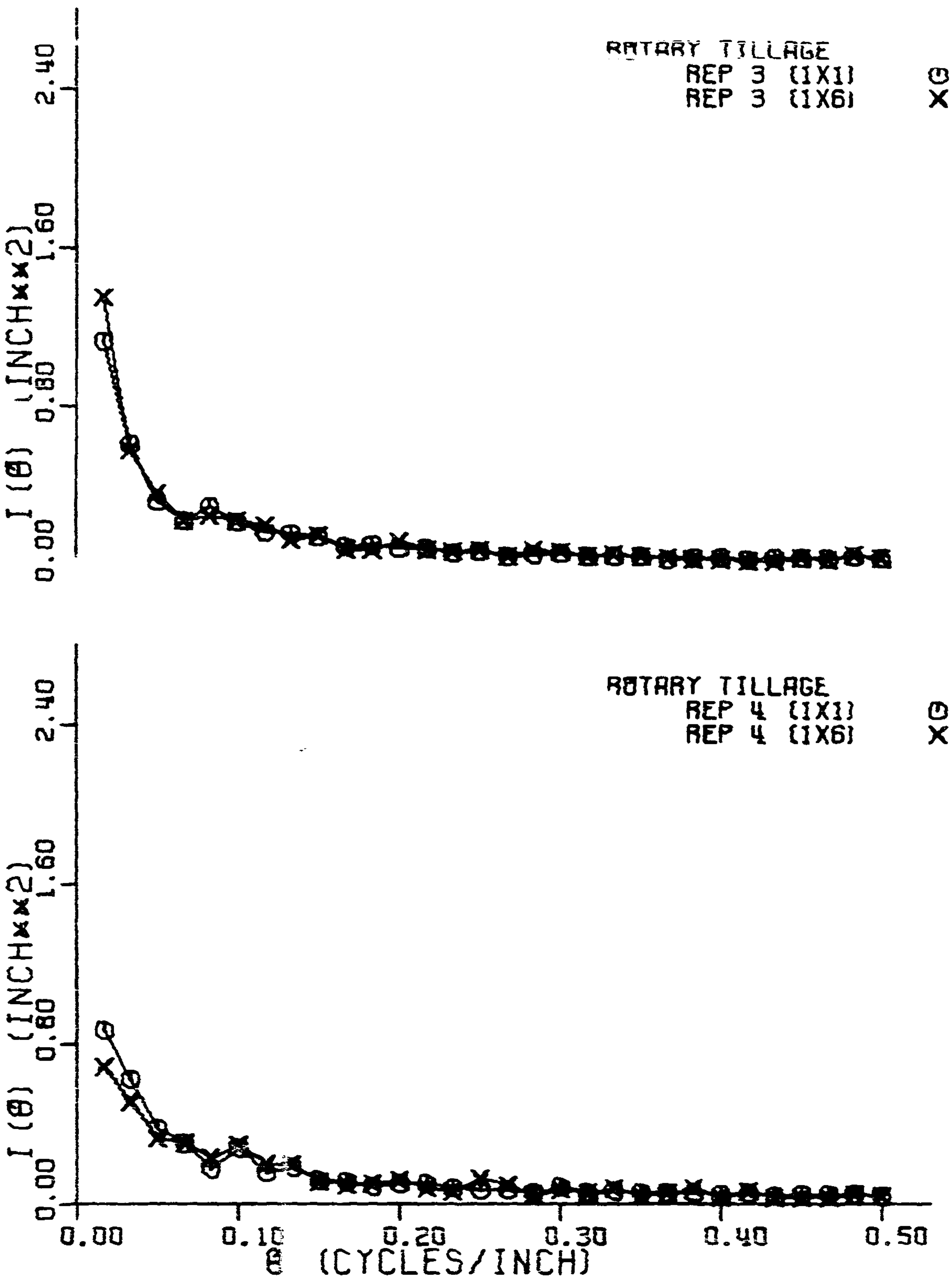


Figure 43. (continued)

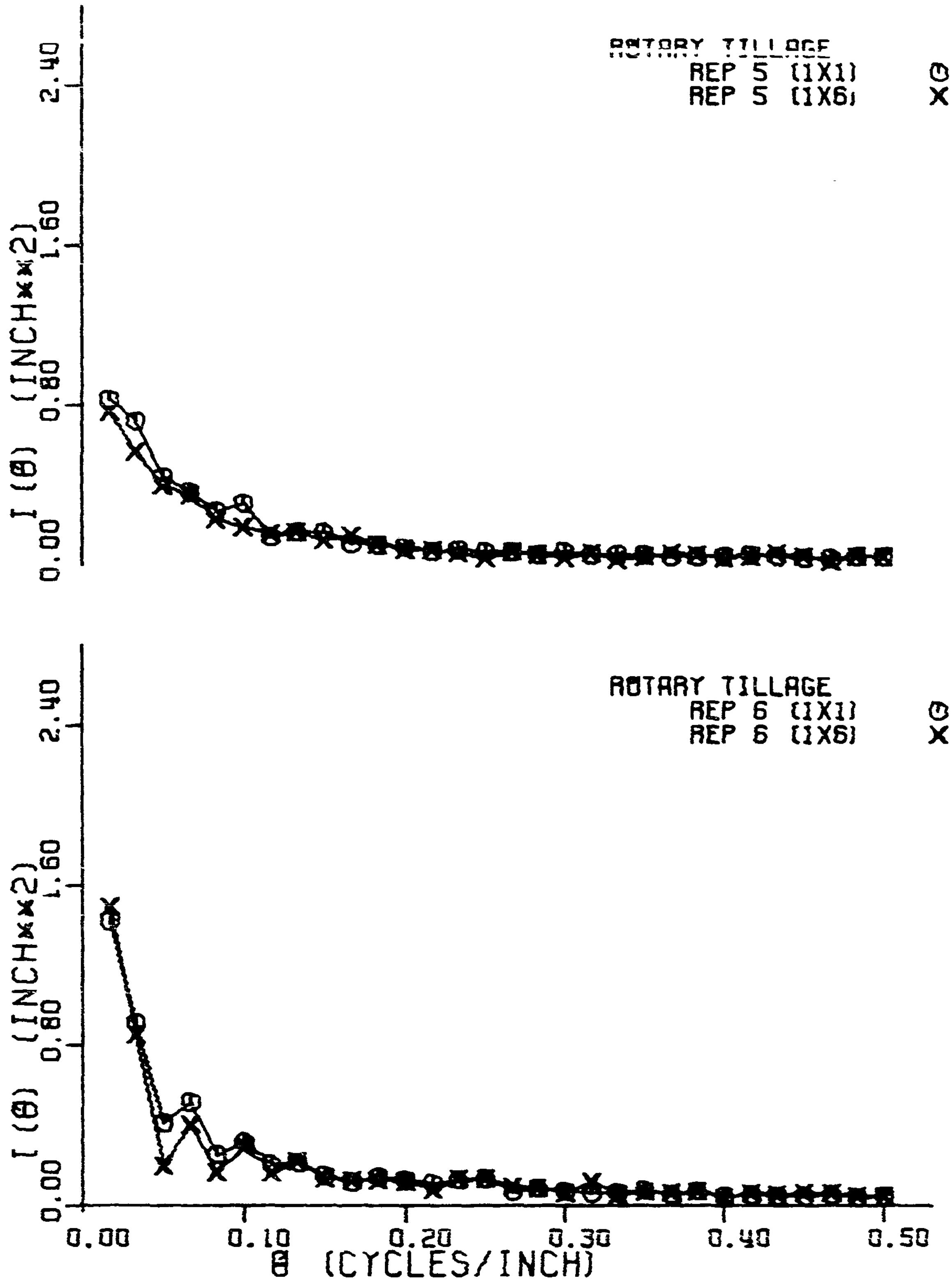
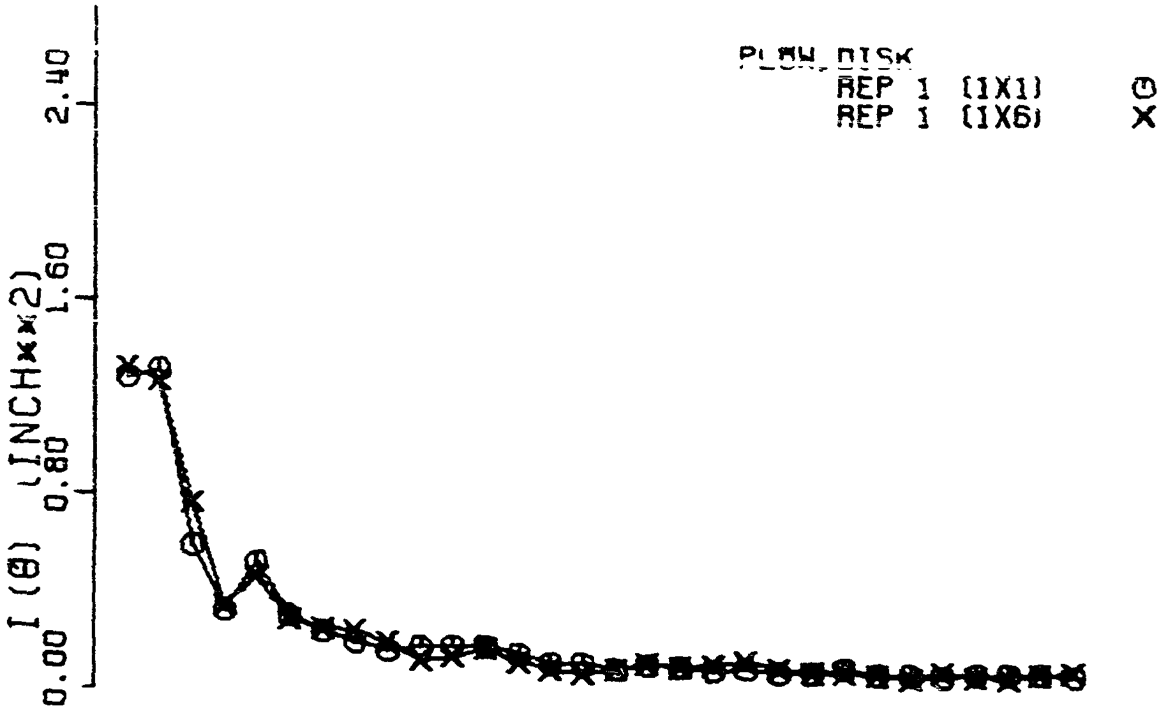


Figure 43. (continued)



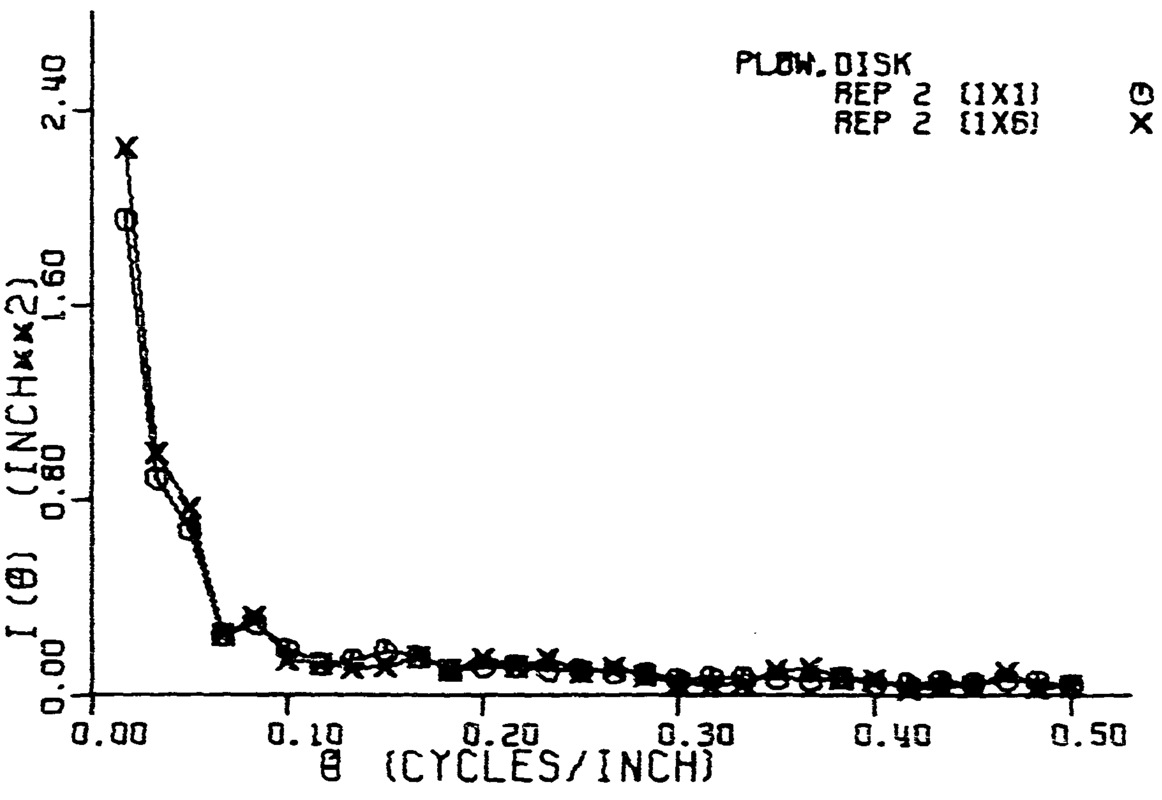


Figure 43. (continued)

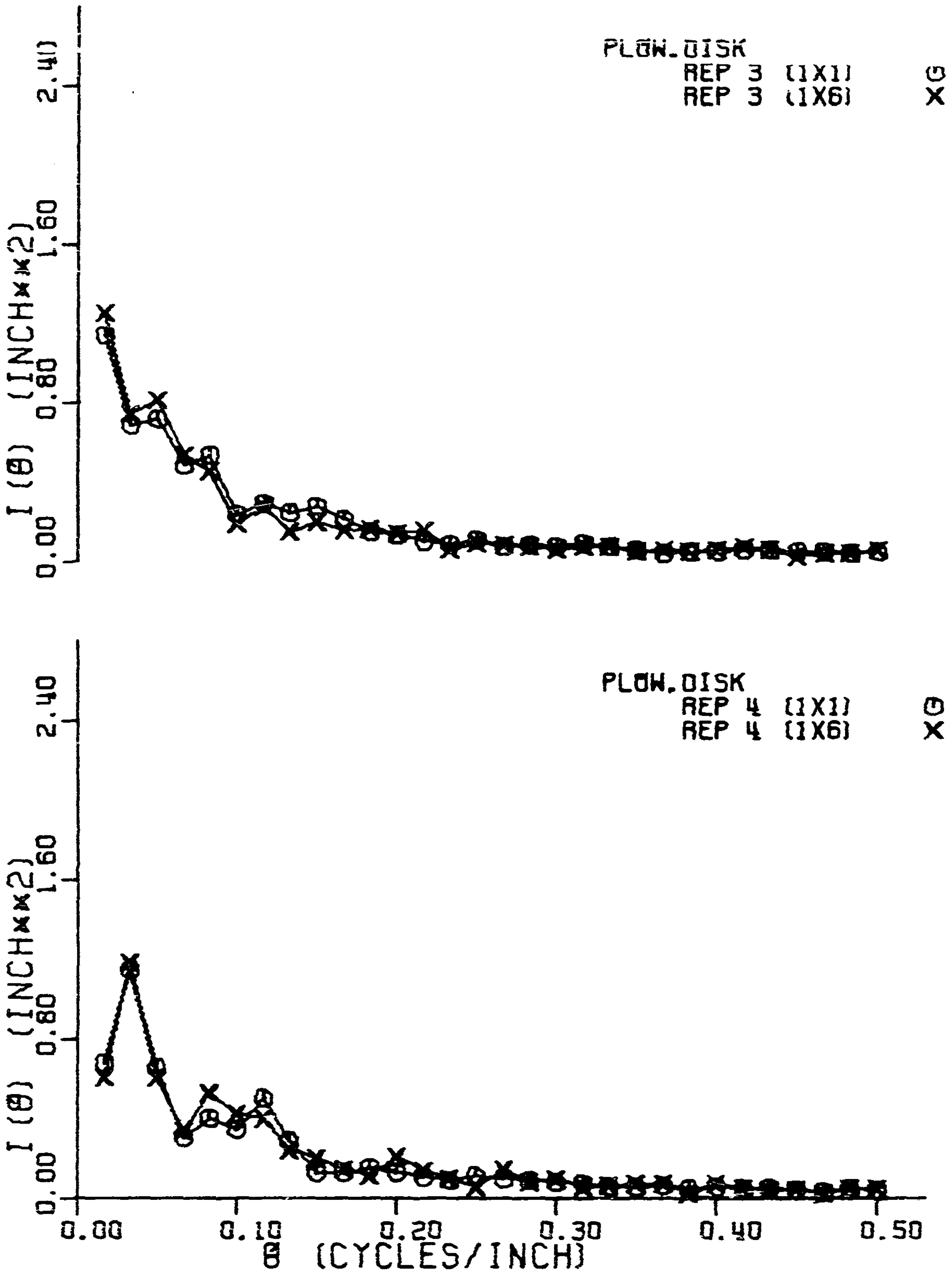


Figure 43. (continued)

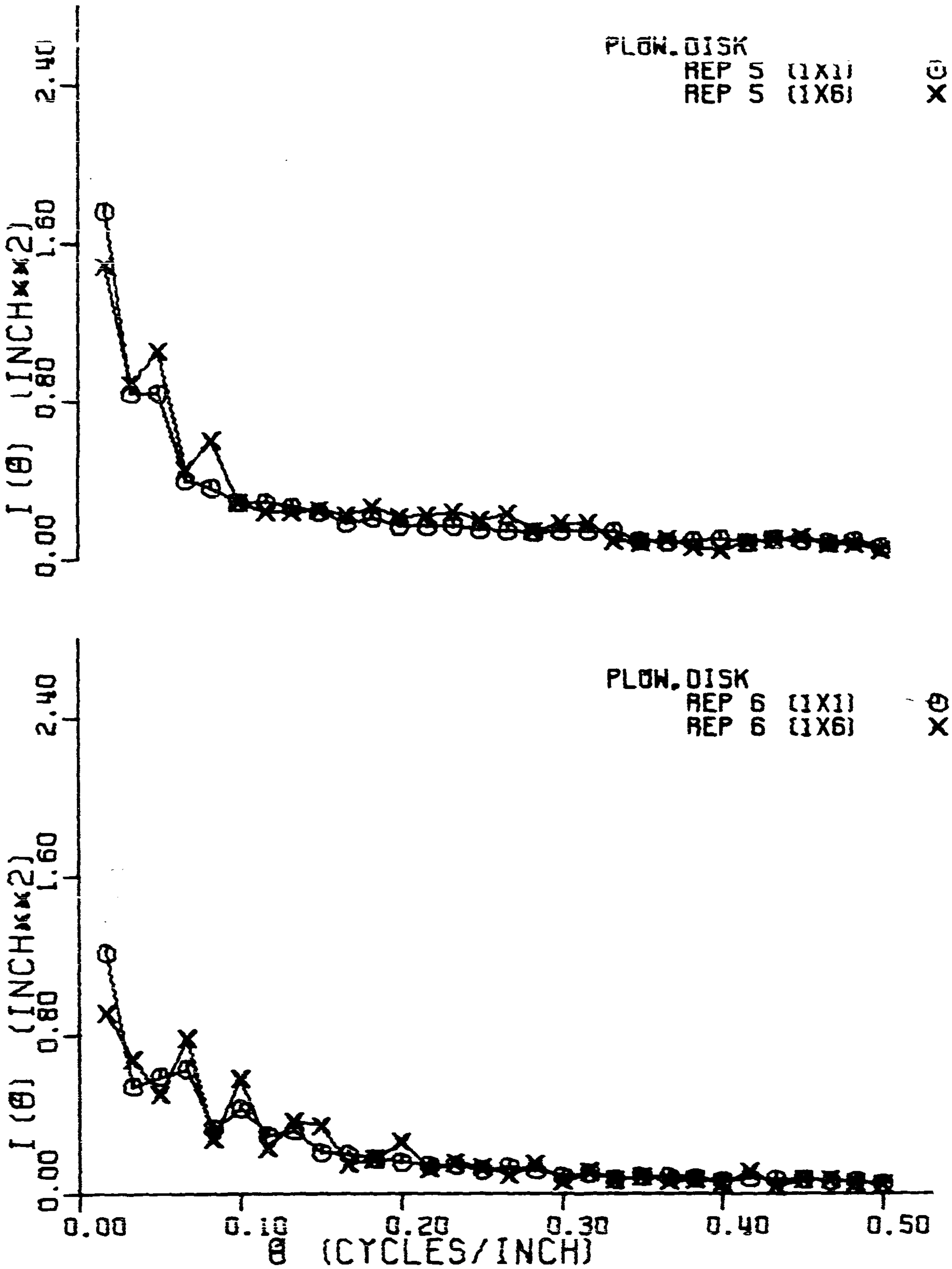


Figure 43. (continued)

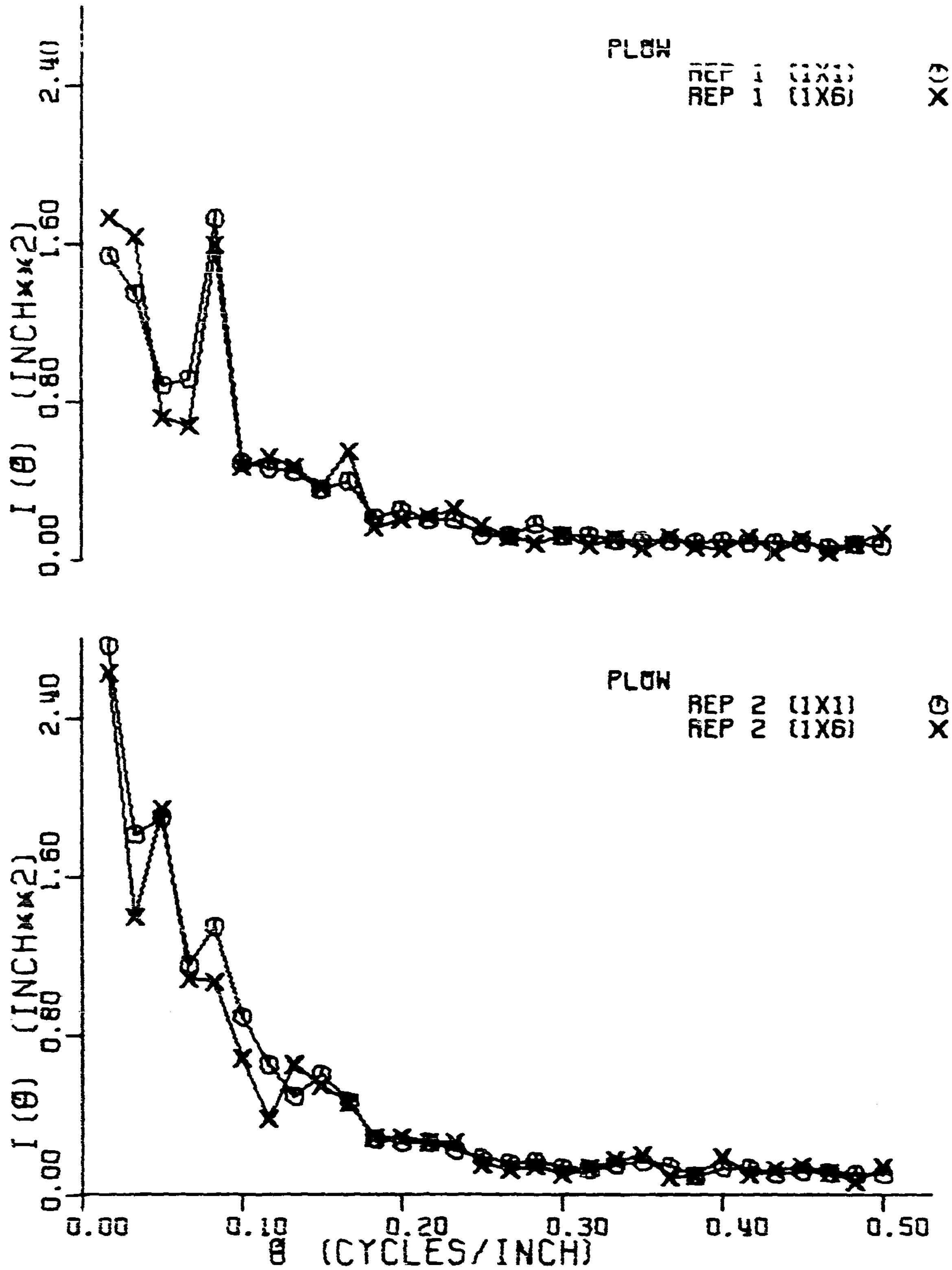


Figure 43. (continued)

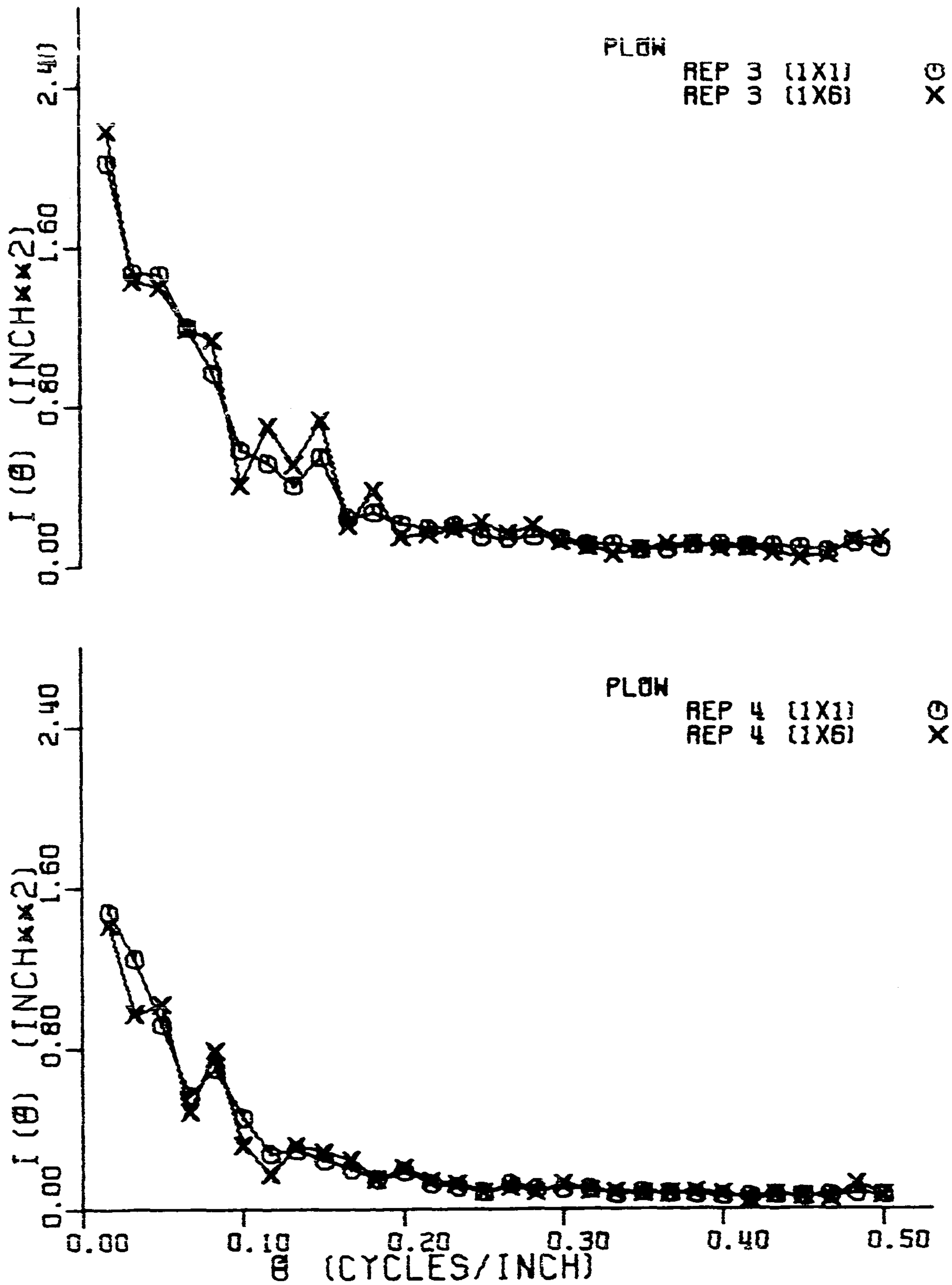


Figure 43. (continued)

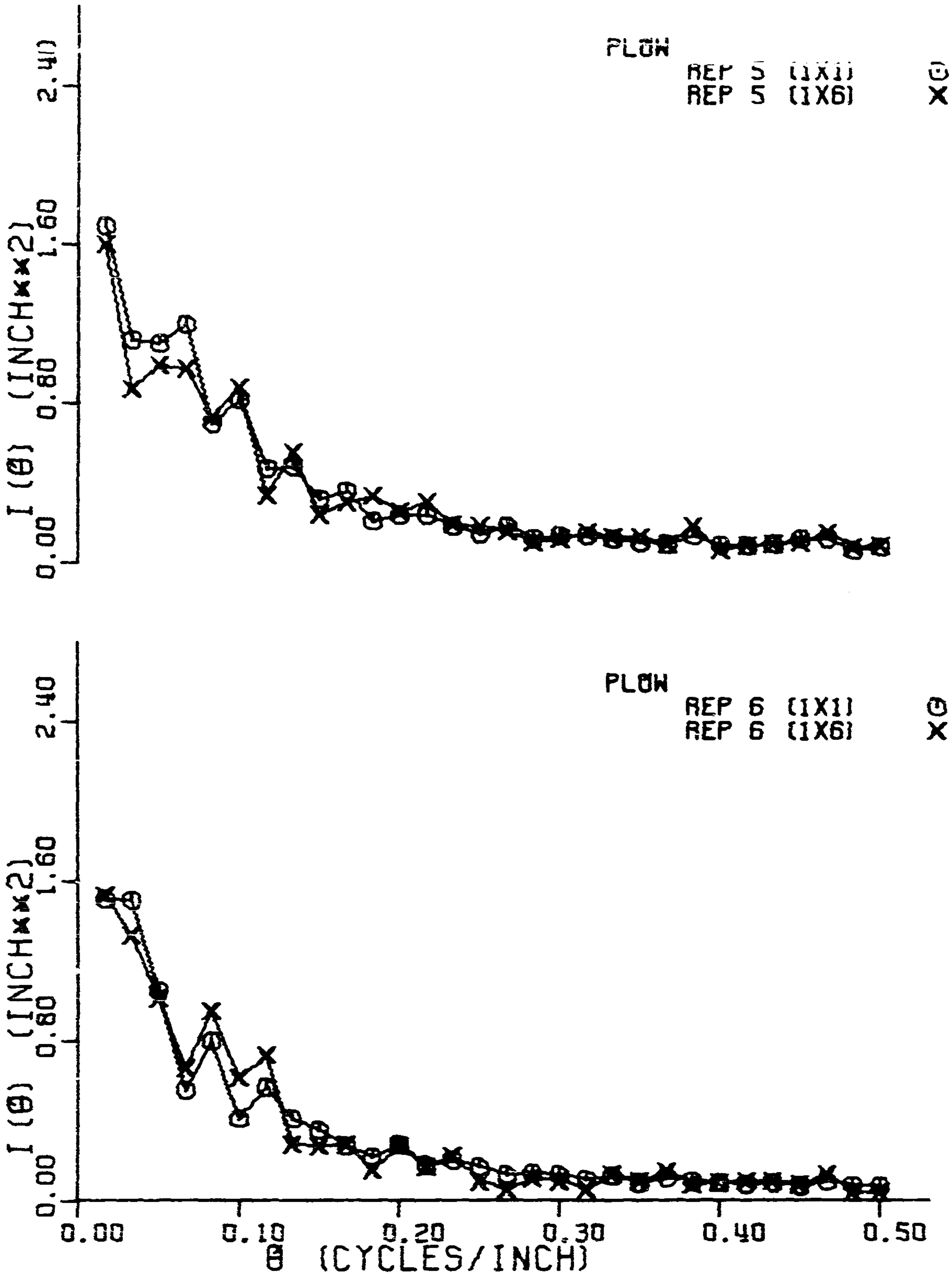
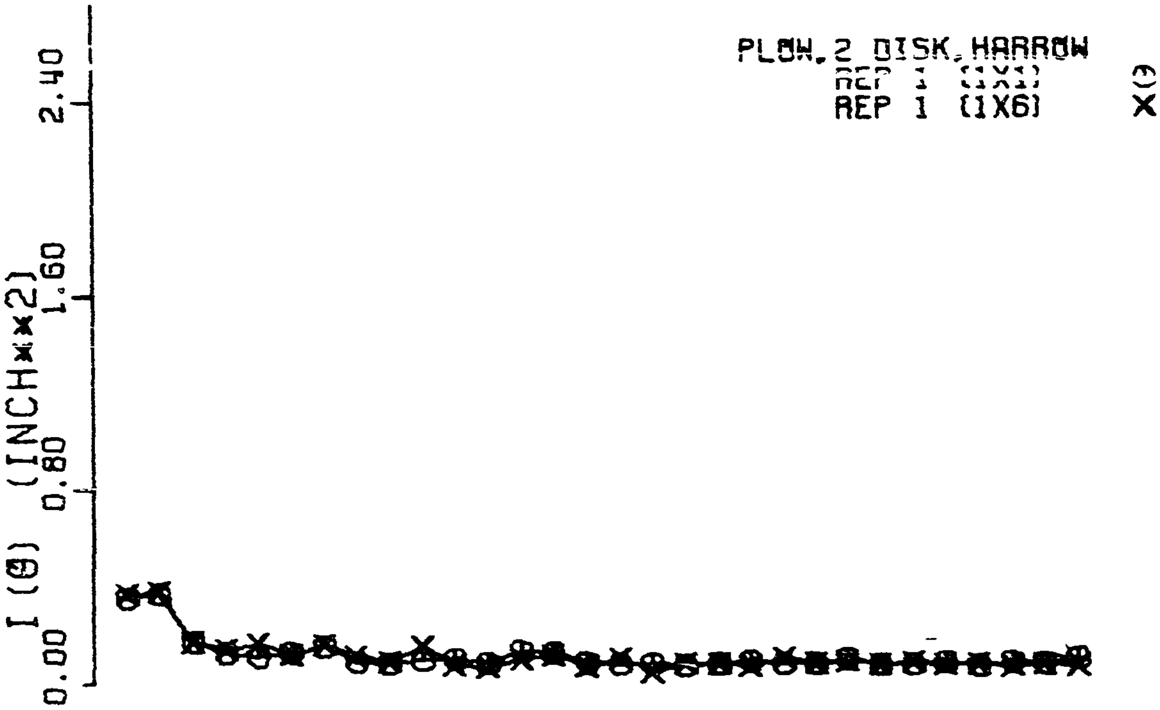


Figure 43. (continued)



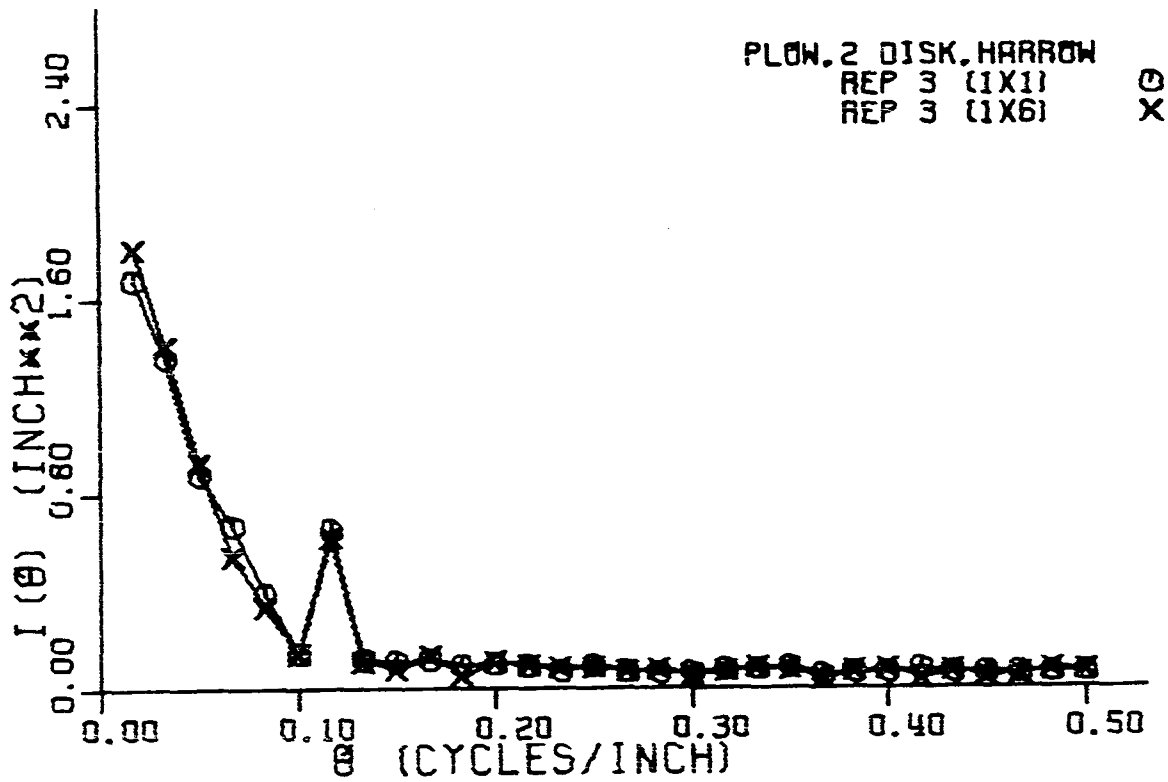


Figure 43. (continued)

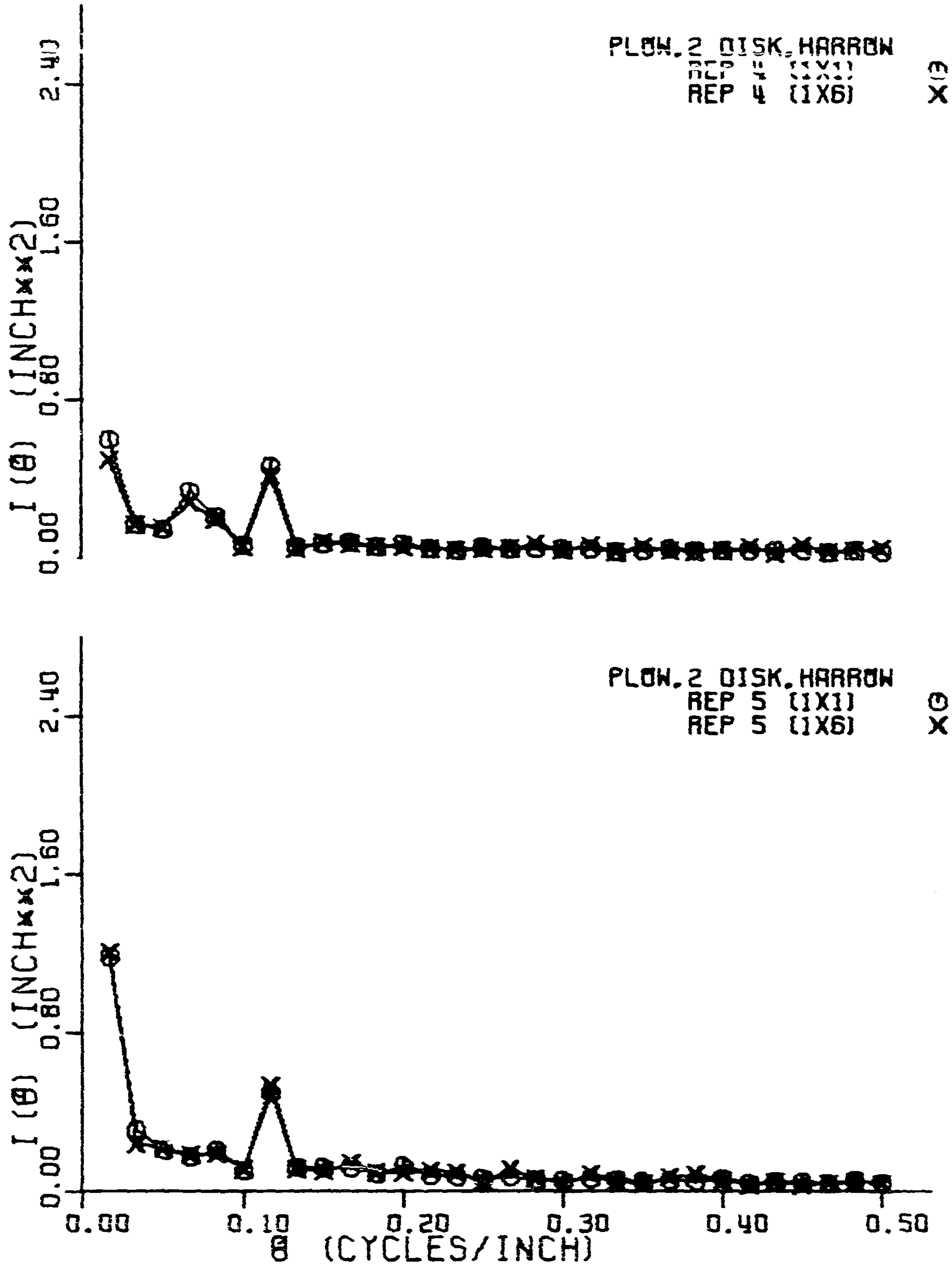


Figure 43. (continued)

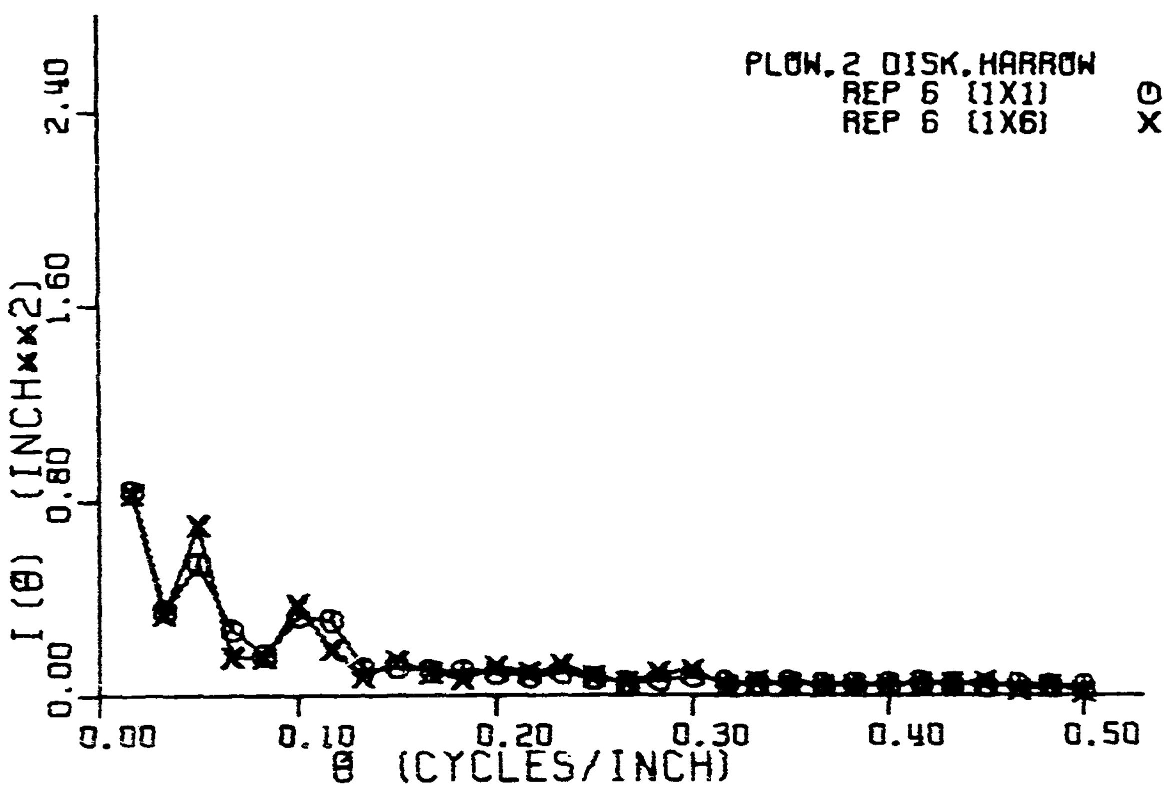


Figure 43. (continued)

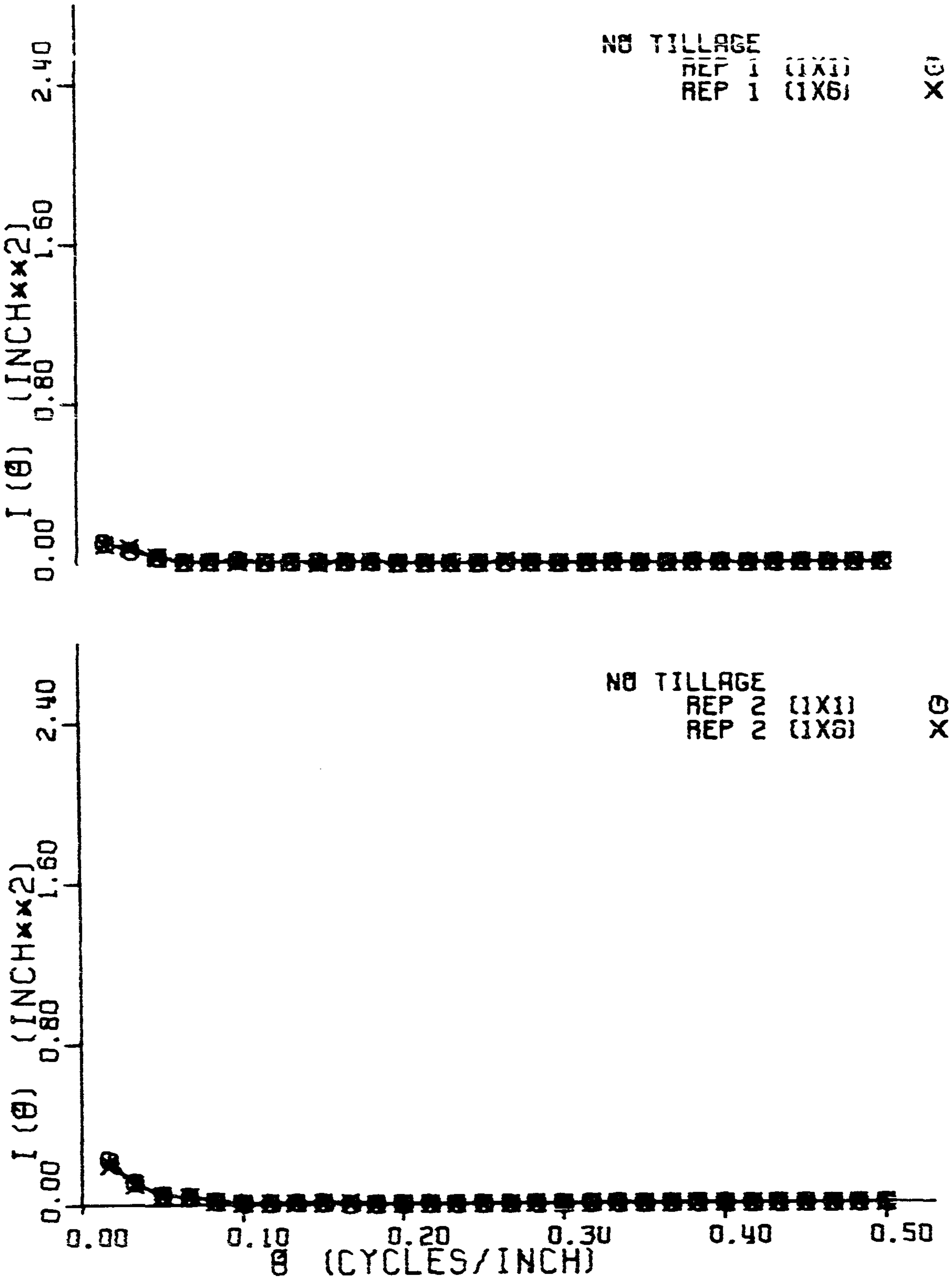


Figure 43. (continued)

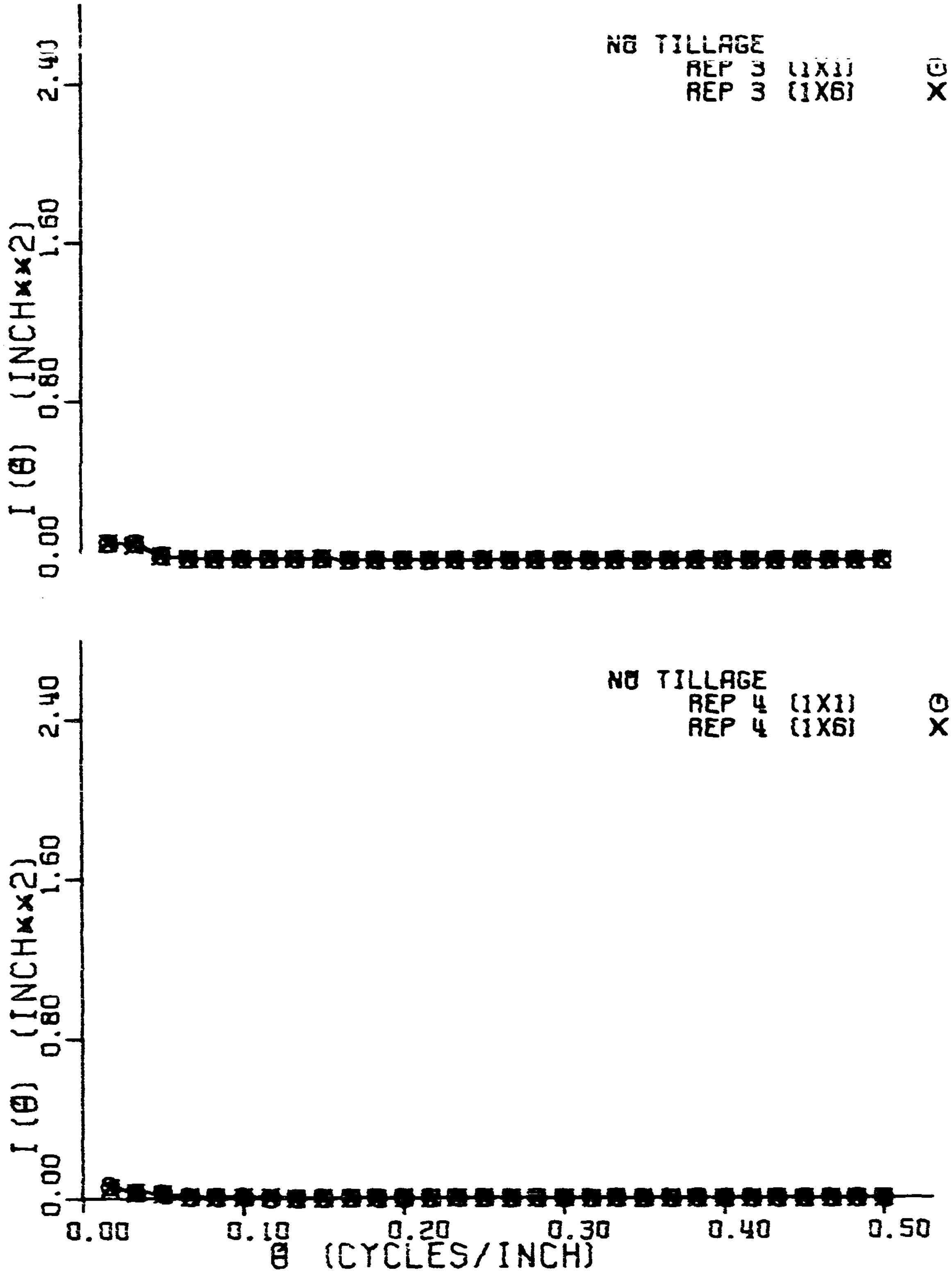


Figure 43. (continued)

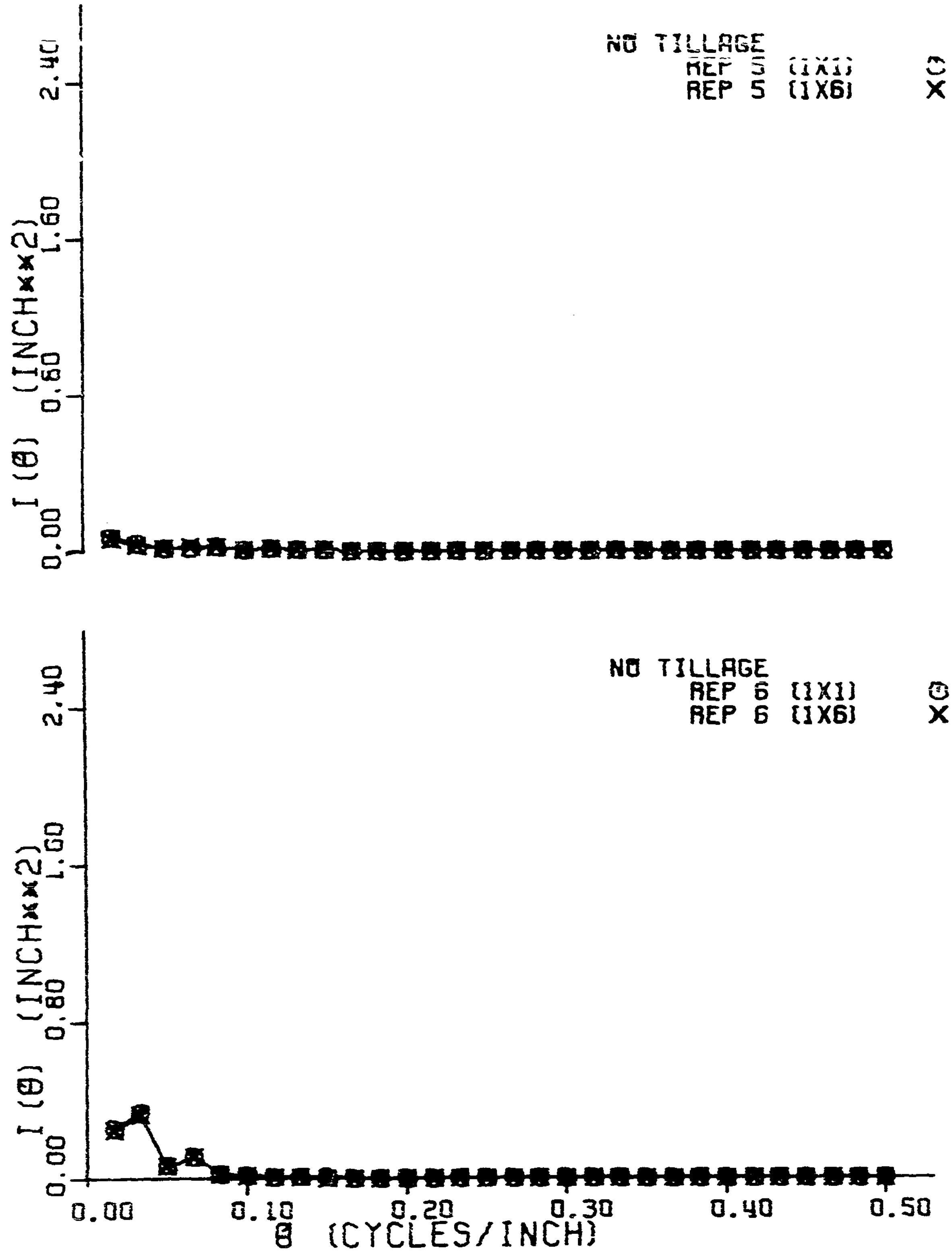


Figure 43. (continued)

APPENDIX C: COMPUTER PROGRAM, RR ROUGHNESS INDEX AND SPECTRAL DENSITY ANALYSIS

```
C
C     CALCULATION OF RR ROUGHNESS INDEX AND PERIODOGRAM
C     ESTIMATES
C
      DIMENSION H(61,84),DE(32,80),XBAR(3),STD(3),RB(3,3),
     1D(3),T(3),ISAVE(3),RY(2),L(2),MV(2),RI(2,2),BB(2),
     2X(2340),RX(9),R(9),RZ(4),HS(60,13),XLAB(5),YLAB(5),
     3DATLAB(5),DT(32),BQ(80),GT(31),DEG(80),W(80),G(80),
     4RE(3,3),B(3),SB(2),ANS(10),GLAB(5)
      DOUBLE PRECISION XBAR,STD,RB,RX,RE,R,B,T,RY,RZ,RI,DET,
     1CHID,XU,XL,XSQU,XSQL,BB,SB,ANS
      EQUIVALENCE(RI(1,1),RZ(1)),(RB(1,1),RX(1)),
     1(RE(1,1),R(1))
      INTEGER CARD,ROE,REP,TREAT,SEQU,XIGN,DA,DA1,DA2
      READ(1,25) NNN,LAG
   25 FORMAT(2I5)
      READ(1,10)XLAB,YLAB
   10 FORMAT(10A4)
      NOPS=60
C     NOPS = NUMBER OF DATA SETS TO BE READ
      ICTP=-1
      IOA=0
      M=3
      ID=1
      NDEP=3
      K=2
      K7=2
      K8=2
      DET=0.0
      IPL=0
   30 ICTP=ICTP+1
      NCD=60
C     NCD = COLUMN LENGTH
      NRD=13
C     NRD = ROW LENGTH
      NC=60
C     NC = NO. READINGS IN A COLUMN
      NCS=1
C     NCS = COLUMN NUMBER OF FIRST READING
      NCI=1
C     NCI = SPACING BETWEEN READINGS WITHIN COLUMNS
      NR=80
C     NR = NO. READINGS IN A ROW (IN DIRECTION OF TILLAGE)
      NRS=4
C     NRS = ROW NUMBER OF FIRST READING
      NRI=6
C     NRI = SPACING BETWEEN READINGS WITHIN ROWS
      IF(ICTP-NOPS)31,999,999
   31 READ (8) CARD,ROE,REP,TREAT,XIGN,ELEV,LOC,DA,DA1,DA2,
     1SEQU,H
```

```
C       READS CARD,ROE,REP,TREAT,XIGN,ELEV,LOC,DA,DA1,DA2,SEQU,
C       AND H UNDER FORMAT (I1,I2,I1,I2,I1,F3.2,5I2,AND 12F5.3)
        IF(MOD(ICTP,2))999,30,32
     32 L2=0
        N=NCD*NRD
        DO 1 I=NCS,NC,NCI
        DO 1 J=NRS,NR,NRI
        L2=L2+1
        X(L2)=I
        X(L2+N)=J
        X(L2+2*N)=H(I,J)
      1 CONTINUE
        ISAVE(1)=1
        ISAVE(2)=2
        CALL CORRE (N,M,IO,X,XBAR,STD,RX,R,B,D,T)
        CALL ORDER (M,R,NDEP,K,ISAVE,RZ,RY)
        CALL UMINV (RZ,K7,K8,DET,L,MV)
        CALL MULTR (N,K,XBAR,STD,B,RZ,RY,ISAVE,BB,SB,T,ANS)
        Z=1.96
        CHID=DSQRT(2.0*ANS(8))
        XL=CHID*Z+ANS(8)
        XU=CHID*(-Z)+ANS(8)
        XSQU=DSQRT(ANS(7)/XU)
        XSQL=DSQRT(ANS(7)/XL)
        WRITE(3,49) TREAT,REP,SEQU
     49 FORMAT(1H1,'   TREAT. NO.',I3,'    REP. NO.',I3,
       1'    SEQU',I3)
        WRITE (3,50)
     50 FORMAT(1H0,' MEANS OF VARIABLES; COLUMNS,ROWS,AND',
       1' HEIGHTS:    X SQUARE LOWER AND UPPER LIMITS')
        WRITE (3,51)XBAR,XSQL,XSQU,XL,XU
     51 FORMAT(1H0,3F15.3,4F15.6)
        WRITE (3,52)
     52 FORMAT(1H0,' STANDARD DEVIATIONS OF VARIABLES')
        WRITE (3,53)STD
     53 FORMAT(1H0,3F15.7)
        WRITE (3,54)
     54 FORMAT(1H0,' REGRESSION COEFFICIENT       STANDARD',
       1' DEVIATION OF B')
        WRITE (3,55)BB(1),SB(1),BB(2),SB(2)
     55 FORMAT(1H0,'COL',F17.7,F30.7,//,' ROW',F17.7,F30.7)
        WRITE (3,56)ANS
     56 FORMAT(1H0, 'INTERCEPT',F20.3,/' MULT. CORR. COEFF',
       1F12.6/' ST. ERROR OF EST.',F12.6,/,' SSAR',F25.6,/,
       2' D. OF F. WITH SSAR',F11.1,/,' M.S. OF SSAR',F17.6,/,
       3' SSDR',F25.6/' D.F.,SSDR',F20.1/' M.S. OF SSDR',
       4F17.6/' F-VALUE',F22.6)
        L4=0
        DO 20 I=1,NCD
        DO 20 J=1,NRD
```

```
      L4=L4+1
      EXVAL=XBAR(3)+B3(1)*(X(L4)-XBAR(1))+B3(2)*
     1(X(L4+N)-XBAR(2))
      HS(I,J)=X(L4+2*N)-EXVAL
   20 CONTINUE
      IPL=IPL+1
      IF(IPL-3)2,3,999
    3 IPL=1
      CALL ORIGIN(0.0,-1.75,4)
    2 CALL SPECTR (HS,NCD,NRD,XLAB,YLAB,GLAB,DATLAB,IPL,BQ,
     1REP,TREAT,SEQU,NNN,LAG,NGP,DT,GT,DEG,W,G)
      GO TO 30
  999 STOP
      END
C
      SUBROUTINE DATA
      RETURN
      END
C
      SUBROUTINE CORRE (N,M,IO,X,XBAR,STD,RX,R,B,D,T)
C
      DIMENSION X(1),XBAR(1),STD(1),RX(1),R(1),B(1),D(1),T(1)
      DOUBLE PRECISION XBAR,STD,RX,R,B,T,DSQRT,DABS
      DO 100 J=1,M
      B(J)=0.0
  100 T(J)=0.0
      K=(M*M+M)/2
      DO 102 I=1,K
  102 R(I)=0.0
      FN=N
      L=0
      IF(IO) 105, 127, 105
  105 DO 108 J=1,M
      DO 107 I=1,N
      L=L+1
  107 T(J)=T(J)+X(L)
      XBAR(J)=T(J)
  108 T(J)=T(J)/FN
      DO 115 I=1,N
      JK=0
      L=I-N
      DO 110 J=1,M
      L=L+N
      D(J)=X(L)-T(J)
  110 B(J)=B(J)+D(J)
      DO 115 J=1,M
      DO 115 K=1,J
      JK=JK+1
  115 R(JK)=R(JK)+D(J)*D(K)
      GO TO 205
```

```
127 IF(N-M) 130, 130, 135
130 KK=N
    GO TO 137
135 KK=M
137 DO 140 I=1,KK
    CALL DATA (M,D)
    DO 140 J=1,M
    T(J)=T(J)+D(J)
    L=L+1
140 RX(L)=D(J)
    FKK=KK
    DO 150 J=1,M
    XBAR(J)=T(J)
150 T(J)=T(J)/FKK
    L=0
    DO 180 I=1,KK
    JK=0
    DO 170 J=1,M
    L=L+1
170 D(J)=RX(L)-T(J)
    DO 180 J=1,M
    B(J)=B(J)+D(J)
    DO 180 K=1,J
    JK=JK+1
180 R(JK)=R(JK)+D(J)*D(K)
    IF(N-KK) 205, 205, 185
185 KK=N-KK
    DO 200 I=1,KK
    JK=0
    CALL DATA (M,D)
    DO 190 J=1,M
    XBAR(J)=XBAR(J)+D(J)
    D(J)=D(J)-T(J)
190 B(J)=B(J)+D(J)
    DO 200 J=1,M
    DO 200 K=1,J
    JK=JK+1
200 R(JK)=R(JK)+D(J)*D(K)
205 JK=0
    DO 210 J=1,M
    XBAR(J)=XBAR(J)/FN
    DO 210 K=1,J
    JK=JK+1
210 R(JK)=R(JK)-B(J)*B(K)/FN
    JK=0
    DO 220 J=1,M
    JK=JK+J
220 STD(J)=DSQRT(DABS(R(JK)))
    DO 230 J=1,M
    DO 230 K=J,M
```

```
      JK=J+(K*K-K)/2
      L=M*(J-1)+K
      RX(L)=R(JK)
      L=M*(K-1)+J
      RX(L)=R(JK)
      IF(STD(J)*STD(K)) 225, 222, 225
  222 R(JK)=0.0
      GO TO 230
  225 R(JK)=R(JK)/(STD(J)*STD(K))
  230 CONTINUE
      FN=SQRT(FN-1.0)
      DO 240 J=1,M
  240 STD(J)=STD(J)/FN
      L=-M
      DO 250 I=1,M
      L=L+M+1
  250 B(I)=RX(L)
      RETURN
      END
C
      SUBROUTINE ORDER (M,R,NDEP,K,ISAVE,RX,RY)
C
      DIMENSION R(1),ISAVE(1),RX(1),RY(1)
      DOUBLE PRECISION R,RX,RY
      MM=0
      DO 130 J=1,K
      L2=ISAVE(J)
      IF(NDEP-L2) 122, 123, 123
  122 L=NDEP+(L2*L2-L2)/2
      GO TO 125
  123 L=L2+(NDEP*NDEP-NDEP)/2
  125 RY(J)=R(L)
      DO 130 I=1,K
      L1=ISAVE(I)
      IF(L1-L2) 127, 128, 128
  127 L=L1+(L2*L2-L2)/2
      GO TO 129
  128 L=L2+(L1*L1-L1)/2
  129 MM=MM+1
  130 RX(MM)=R(L)
      ISAVE(K+1)=NDEP
      RETURN
      END
C
      SUBROUTINE MINV(A,N,NN,D,L,M)
C
      DIMENSION A(1),L(1),M(1)
      DOUBLE PRECISION A,D,BIGA,HOLD,DABS
      D=1.0
      NK=-NN
```

```
      DO 80 K=1,N
      NK=NK+NN
      L(K)=K
      M(K)=K
      KK=NK+K
      BIGA=A(KK)
      DO 20 J=K,N
      IZ=NN*(J-1)
      DO 20 I=K,N
      IJ=IZ+I
   10 IF(DABS(BIGA)-DABS(A(IJ))) 15,20,20
   15 BIGA=A(IJ)
      L(K)=I
      M(K)=J
   20 CONTINUE
      J=L(K)
      IF(J-K) 35,35,25
   25 KI=K-NN
      DO 30 I=1,N
      KI=KI+NN
      HOLD=-A(KI)
      JI=KI-K+J
      A(KI)=A(JI)
   30 A(JI) =HOLD
   35 I=M(K)
      IF(I-K) 45,45,38
   38 JP=NN*(I-1)
      DO 40 J=1,N
      JK=NK+J
      JI=JP+J
      HOLD=-A(JK)
      A(JK)=A(JI)
   40 A(JI) =HOLD
   45 IF(BIGA) 48,46,48
   46 D=0.0
      RETURN
   48 DO 55 I=1,N
      IF(I-K) 50,55,50
   50 IK=NK+I
      A(IK)=A(IK)/(-BIGA)
   55 CONTINUE
      DO 65 I=1,N
      IK=NK+I
      HOLD=A(IK)
      IJ=I-NN
      DO 65 J=1,N
      IJ=IJ+NN
      IF(I-K) 60,65,60
   60 IF(J-K) 62,65,62
   62 KJ=IJ-I+K
```

```
      A(IJ)=HOLD*A(KJ)+A(IJ)
   65 CONTINUE
      KJ=K-NN
      DO 75 J=1,N
      KJ=KJ+NN
      IF(J-K) 70,75,70
   70 A(KJ)=A(KJ)/BIGA
   75 CONTINUE
      D=D*BIGA
      A(KK)=1.0/BIGA
   80 CONTINUE
      K=N
  100 K=(K-1)
      IF(K) 150,150,105
  105 I=L(K)
      IF(I-K) 120,120,108
  108 JQ=NN*(K-1)
      JR=NN*(I-1)
      DO 110 J=1,N
      JK=JQ+J
      HOLD=A(JK)
      JI=JR+J
      A(JK)=-A(JI)
  110 A(JI) =HOLD
  120 J=M(K)
      IF(J-K) 100,100,125
  125 KI=K-NN
      DO 130 I=1,N
      KI=KI+NN
      HOLD=A(KI)
      JI=KI-K+J
      A(KI)=-A(JI)
  130 A(JI) =HOLD
      GO TO 100
  150 RETURN
      END
C
      SUBROUTINE MULTR(N,K,XBAR,STD,D,RX,RY,ISAVE,B,SB,T,ANS)
C
      DIMENSION XBAR(1),STD(1),D(1),RX(1),RY(1),ISAVE(1),
     1B(1),SB(1),T(1),ANS(1)
      DOUBLE PRECISION XBAR,STD,D,RX,RY,B,SB,T,ANS,RM,BO,
     1SSAR,SSDR,SY,DSQRT,DABS,FN,FK,SSARM,SSDRM,F
      MM=K+1
      DO 100 J=1,K
  100 B(J)=0.0
      DO 110 J=1,K
      L1=K*(J-1)
      DO 110 I=1,K
      L=L1+I
```

```
  110 B(J)=B(J)+RY(I)*RX(L)
      RM=0.0
      BO=0.0
      L1=ISAVE(MM)
      DO 120 I=1,K
      RM=RM+B(I)*RY(I)
      L=ISAVE(I)
      B(I)=B(I)*(STD(L1)/STD(L))
  120 BO=BO+B(I)*XBAR(L)
      BO=XBAR(L1)-BO
      SSAR=RM*D(L1)
  122 RM=DSQRT(DABS(RM))
      SSDR=D(L1)-SSAR
      FN=N-K-1
      SY=SSDR/FN
      DO 130 J=1,K
      L1=K*(J-1)+J
      L=ISAVE(J)
  125 SB(J)=DSQRT(DABS((RX(L1)/D(L))*SY))
  130 T(J)=B(J)/SB(J)
  135 SY=DSQRT(DABS(SY))
      FK=K
      SSARM=SSAR/FK
      SSDRM=SSDR/FN
      F=SSARM/SSDRM
      ANS(1)=BO
      ANS(2)=RM
      ANS(3)=SY
      ANS(4)=SSAR
      ANS(5)=FK
      ANS(6)=SSARM
      ANS(7)=SSDR
      ANS(8)=FN
      ANS(9)=SSDRM
      ANS(10)=F
      RETURN
      END
C
      SUBROUTINE SPECTR (H,NC,NR,XLAB,YLAB,GLAB,DATLAB,IPL,
     1B,GT,DEG,W,G,REP,TREAT,SEQU,N,LAG,NGP,DT)
C
      DIMENSION H(60,1),XLAB(1),YLAB(1),GLAB(5),DATLAB(5),
     1GT(1),DEG(1),W(1),G(1),DT(1),AL(1),B(1)
      INTEGER REP,TREAT,SEQU
      NI=NC*NR
      CN=FLOAT(NC)
      RN=FLOAT(NR)
      TN=FLOAT(NI)
      R1=0.0
      R2=0.0
```

```
      AN=FLOAT(N)
      J=0
      DO 110 I=1,60
  110 GT(I)=0.0
      DO 111 K3=1,NR
      IP=0
  730 SUMP=0.0
      IMAX=N-IP
      DO 740 I=1,IMAX
      L=I+IP
  740 SUMP=SUMP+H(I,K3)*H(L,K3)
      P=IP
      W(IP+1)=SUMP/AN
      IF(LAG-IP-1)750,750,760
  760 IP=IP+1
      GO TO 730
  750 J=0
      LAG2=LAG/2
      LAG3=LAG2+1
      LAGP=LAG3+1
      LAG4=LAG2-2
      LAG5=LAG2-1
      AG=LAG
  755 SUMW=0.0
      FJ=J
      KAG=LAG-1
      DO 770 K=1,KAG
      FK=K
  770 SUMW=SUMW+W(K+1)*COS(6.28318*FK*FJ/AN)
      DEG(J+1)=FJ/AN
      G(J+1)=.318310*(W(1)+2.0*SUMW)
      IF(J-LAG2)775,803,803
  775 J=J+1
      GO TO 755
  803 R1=R1+W(2)/W(1)
      R2=R2+W(3)/W(1)
      DO 109 I=1,LAG3
      GT(I)=GT(I)+G(I)
  109 CONTINUE
  111 CONTINUE
      DO 112 I=1,LAG3
      GT(I)=GT(I)/RN
  112 CONTINUE
      R1=R1/NR
      R2=R2/NR
      WRITE(3,710)R1,R2
  710 FORMAT('0    AUTOCORRELATIONS     R1=',F7.5,'      R2=',
     1F7.5)
      WRITE(3,718)
  718 FORMAT(1H ,9X,'DEGREES',13X,'AVERAGE DENSITY')
```

```
      WRITE(3,719)(DEG(I),GT(I),I=1,LAG3)
  719 FORMAT(10X,F5.1,15X,E11.5)
      GT(1)=0.0
      READ(1,10)GLAB,DATLAB
   10 FORMAT(10A4)
      IF(IPL-2)2,3,3
    2 CALL ORIGIN (8.5,5.75,2)
      CALL GRAPH(LAG3,DEG,DT,1,-103,5.3,3.50,0.1,0.,.8,0.,
     1XLAB,YLAB,GLAB,DATLAB)
      READ(1,10)GLAB,DATLAB
      CALL GRAPH (LAG3,DEG,GT,4,-103,0.,0.,0.,0.,0.,0.,0.,0.,
     10.,DATLAB)
      GO TO 512
    3 CALL ORIGIN(0.0,-4.0,1)
      CALL GRAPH(LAG3,DEG,DT,1,-103,5.3,3.50,0.1,0.,.8,0.,
     1XLAB,YLAB,GLAB,DATLAB)
      READ(1,10)GLAB,DATLAB
      CALL GRAPH (LAG3,DEG,GT,4,-103,0.,0.,0.,0.,0.,0.,0.,0.,
     10.,DATLAB)
  512 CONTINUE
      RETURN
  999 STOP
      END
```

APPENDIX D: COMPUTER PROGRAM, RM ROUGHNESS INDEX

```
C
C     CALCULATION OF SURFACE ROUGHNESS COEFFICIENTS USING
C     METHOD DEVELOPED BY LUTTRELL
C
      DIMENSION IS(61,84), IREP1(2),TRET1(1,2),IR1(1,80),
     1IR2(1,80),IR3(1,80),IR10(1,80),IR20(1,80),JR1(1,80),
     2JR3(1,80),JR10(1,80),JR20(1,80),ITIR(1,80),ITJR(1,80),
     3IMDTR(1,1),IP(61),IDAY(2),MON(2),IYR(2),ROW(60),ID(30),
     4JR2(1,80),IDTR(1,80),ABD(3,30),ABO(3,30)
      REAL IR,IP,ITIR,ITJR,IDTR,ISUM,IMDTR,IR1,IR2,IR3,IR10,
     1IR20,JR1,JR2,JR3,JR10,JR20,IS
      INTEGER REP,TREAT,CARD,ROW,SINE,FIELD,SEQU,TRET1,CT,
     1CT1,DA1,DA2,DA3
      DO 93 I=1,30
      DO 93 J=1,3
      ABO(J,I)=0.0
   93 CONTINUE
      L=0
      DO 94 J=1,5
      DO 94 I=1,6
      L=L+1
      ID(L)=I
   94 CONTINUE
      NOR=0
      NODS=60
      COL=80.0
      NCOL=80
  190 IF(NOR-NODS)180,600,109
  180 READ(8)CARD,IRW,REP,TREAT,SINE,ELV,FIELD,DA1,DA2,DA3,
C
C     FORMAT USED  (I1,I2,I1,I2,I1,F3.2,5I2,AND 12F5.3)
C
     1SEQU,IS
      NOR=NOR+1
      IF(MOD(NOR,2))109,108,107
  107 J1=1
      K2=1
      GO TO 888
  108 J1=2
      K2=2
  888 ICT=0
      I6=0
      I5=1
  300 ICT=ICT+1
      I6=I6+1
      DO 309 K8=1,60
      IP(K8)=IS(K8,ICT)
  309 CONTINUE
      GO TO (105,106),J1
  105 IDAY(I)=DA1
```

```
      MON(1)=DA2
      IYR(1)=DA3
      GO TO 111
  106 IDAY(2)=DA1
      MON(2)=DA2
      IYR(2)=DA3
  111 IREP1(K2)=REP
      TRET1(I5,K2)=TREAT
      GO TO (112,113),J1
  112 IR1(I5,I6)=0
      I=1
      DO 5 I=1,58
      IR=IP(I)-2*IP(I+1)+IP(I+2)
      IR=ABS(IR)
    4 IR1(I5,I6)=IR1(I5,I6)+IR
    5 CONTINUE
      J=1
      IR2(I5,I6)=0
      DO 6 J=1,56,2
   15 IR=IP(J)-2*IP(J+2)+IP(J+4)
      IR=ABS(IR)
   12 IR2(I5,I6)=IR2(I5,I6)+IR
    6 CONTINUE
   19 IR=IP(57)-2*IP(59)+IP(60)
      IR=ABS(IR)
      IR2(I5,I6)=IR2(I5,I6)+IR
  114 K=1
      IR3(I5,I6)=0
      DO 21 K=1,54,3
   30 IR=IP(K)-2*IP(K+3)+IP(K+6)
      IR=ABS(IR)
   33 IR3(I5,I6)=IR3(I5,I6)+IR
   21 CONTINUE
      IR=IP(55)-2*IP(58)+IP(60)
      IR=ABS(IR)
      IR3(I5,I6)=IR3(I5,I6)+IR
  115 L=1
      IR10(I5,I6)=0
      DO 37 L=1,32,10
   40 IR=IP(L)-2*IP(L+10)+IP(L+20)
      IR=ABS(IR)
   42 IR10(I5,I6)=IR10(I5,I6)+IR
   37 CONTINUE
      IR=IP(41)-2*IP(51)+IP(60)
      IR=ABS(IR)
      IR10(I5,I6)=IR10(I5,I6)+IR
  116 M=1
      IR20(I5,I6)=0
   51 IR=IP(M)-2*IP(M+20)+IP(M+40)
   52 IR=ABS(IR)
```

```
 54 IR20(I5,I6)=IR20(I5,I6)+IR
    IF(M-21)55,117,117
 55 M=M+20
    IF(M-21)51,56,56
 56 IR=IP(M)-2*IP(M+20)+IP(60)
    GO TO 52
113 JR1(I5,I6)=0
    DO 705 I=1,58
    IR=IP(I)-2*IP(I+1)+IP(I+2)
    IR=ABS(IR)
704 JR1(I5,I6)=JR1(I5,I6)+IR
705 CONTINUE
706 J=1
    JR2(I5,I6)=0
    DO 645 J=1,56,2
715 IR=IP(J)-2*IP(J+2)+IP(J+4)
    IR=ABS(IR)
712 JR2(I5,I6)=JR2(I5,I6)+IR
645 CONTINUE
    IR=IP(57)-2*IP(59)+IP(60)
    IR=ABS(IR)
    JR2(I5,I6)=JR2(I5,I6)+IR
120 K=1
    JR3(I5,I6)=0
    DO 737 K=1,54,3
730 IR=IP(K)-2*IP(K+3)+IP(K+6)
    IR=ABS(IR)
733 JR3(I5,I6)=JR3(I5,I6)+IR
737 CONTINUE
    IR=IP(55)-2*IP(58)+IP(60)
    IR=ABS(IR)
    JR3(I5,I6)=JR3(I5,I6)+IR
121 L=1
    JR10(I5,I6)=0
740 IR=IP(L)-2*IP(L+10)+IP(L+20)
745 IR=ABS(IR)
742 JR10(I5,I6)=JR10(I5,I6)+IR
    L=L+10
    IF (L-41)740,744,122
744 IR=IP(L)-2*IP(L+10)+IP(60)
    GO TO 745
122 M=1
    JR20(I5,I6)=0
751 IR=IP(M)-2*IP(M+20)+IP(M+40)
752 IR=ABS(IR)
754 JR20(I5,I6)=JR20(I5,I6)+IR
755 M=M+20
    IF (M-21)751,756,117
756 IR=IP(M)-2*IP(M+20)+IP(60)
    GO TO 752
```

```
117 IF(ICT-80)300,200,109
200 IF(J1-1)109,190,204
204 J5=1
    DO 205 J6=1,80
    ITIR(J5,J6)=IR1(J5,J6)+IR2(J5,J6)+IR3(J5,J6)
   1+IR10(J5,J6)+IR20(J5,J6)
    ITJR(J5,J6)=JR1(J5,J6)+JR2(J5,J6)+JR3(J5,J6)
   1+JR10(J5,J6)+JR20(J5,J6)
    IDTR(J5,J6)=ITJR(J5,J6)-ITIR(J5,J6)
205 CONTINUE
    SBFR=0.0
    SAFT=0.0
    ISUM=0.0
    DO 208 J6=1,80
    SBFR=SBFR+ITIR(J5,J6)
    SAFT=SAFT+ITJR(J5,J6)
    ISUM=ISUM+IDTR(J5,J6)
208 CONTINUE
    RB=SBFR/COL
    RA=SAFT/COL
    IMDTR(1,1)=ISUM/80.0
    II=NOR/2
    ABD(1,II)=RB
    ABD(2,II)=RA
    ABD(3,II)=IMDTR(1,1)
    GO TO 190
600 WRITE(3,10)
 10 FORMAT('1')
    WRITE(3,20)
 20 FORMAT('0--------------------------------------------',
   1'------------------')
    WRITE(3,50)
 50 FORMAT(' ',21X,'ROUGHNESS COEFFICIENTS IN INCHES')
    WRITE(3,60)
 60 FORMAT('+',21X,'________________________________')
    WRITE(3,70)
 70 FORMAT(' TREAT-',10X,'BEFORE TILLAGE   AFTER TILLAGE',
   1'    DIFFERENCE')
    WRITE(3,80)
 80 FORMAT(' MENT    BLOCK        (RMB)           (RMA)',
   1'          (RMD)')
    WRITE(3,90)
 90 FORMAT(' ','-------------------------------------------',
   1'----------------------')
    DO 91 I=1,15
    DO 91 J=1,3
    ABD(J,I)=ABD(J,I+15)
 91 CONTINUE
    DO 92 I=16,30
    DO 92 J=1,3
```

```
      ABO(J,I)=ABO(J,I-15)
   92 CONTINUE
      ABO(1,20)=10000.0
      ABO(2,20)=10000.0
      ABO(3,20)=10000.0
      WRITE(3,100) (ID(I),(ABO(J,I),J=1,3),I=1,30)
  100 FORMAT('  RT',I8,F15.1,F16.1,F15.1/5(I12,F15.1,F16.1,
     1F15.1/)/'  PD',I8,F15.1,F16.1,F15.1,/,5(I12,F15.1,F16.1
     2,F15.1/)/'  P ',I8,F15.1,F16.1,F15.1/5(I12,F15.1,F16.1,
     3F15.1/)/'  PODH',I6,F15.1,F16.1,F15.1/5(I12,11X,F4.1,
     411X,F5.1,10X,F5.1/)/'  C ',I8,F15.1,F16.1,F15.1/5(I12,
     5F15.1,F16.1,F15.1/))
      WRITE(3,90)
      WRITE(2,765)(I,ID(I),(ABO(J,I),J=1,3),I=1,30)
  765 FORMAT(I2,I3,3F15.3,'                    LUTTRELL')
  109 STOP
      END
```

APPENDIX E: COMPUTER PROGRAM, RL ROUGHNESS INDEX

```
C
C     CALCULATION OF SURFACE ROUGHNESS COEFFICIENTS USING
C     METHOD DEVELOPED BY ALLMARAS, ET AL.
C
      DIMENSION ID(30),ABD(3,30),ABU(3,30)
      DOUBLE PRECISION HL(9601),          SIGNT,SIGT,AV(60),
     1AVNL(80),GAL,SUMX,SUMY,SUMXY,SUMX2,CONX,CONY,A,B,C,
     2Y(131),R,SUM,X(131),YP(131),YPH(131),BP,Z,Z2,AVN(80),
     3YH(131)
      INTEGER CARD,ROW,REP,TREAT,DATE,SEQU
      DO 106 I=1,30
      DO 106 J=1,3
      ABD(J,I)=0.0
  106 CONTINUE
      L=0
      DO 107 J=1,5
      DO 107 I=1,6
      L=L+1
      ID(L)=I
  107 CONTINUE
      LA=6
      MA=1
      NOC=0
      NODS=60
   30 NEST=0
      NOC=NOC+1
C     NEST=1 IF INTERMEDIATE CALCULATIONS ARE TO BE PRINTED,
C     OTHERWISE NEST=0
      NPAGE=0
      NR=80
C     NR=NUMBER OF READINGS TAKEN IN DIRECTION OF TILLAGE
      NC=60
C     NC=NUMBER OF READINGS TAKEN PERPENDICULAR TO TILLAGE
      NI=NC*NR
      NROW=NR-1
      NCOL=NC-1
      NIL=NI-1
      CN=DFLOAT(NC)
      RN=DFLOAT(NR)
      TN=DFLOAT(NI)
      SPR=1
C     SPR=SPACE (IN INCHES) BETWEEN READINGS ALONG ROWS
      SPC=1
C     SPC=SPACE (IN INCHES) BETWEEN READINGS ACROSS ROWS
      SPRN=SPR*(RN-1.0)
      SPCN=SPC*(CN-1.0)
      RNSP=RN*SPR
      CNSP=CN*SPC
      L=1
      LL=80
```

```
      DO 1 I=1,60
      READ(8,100)CARD,ROW,REP,TREAT,XIGN,ELEV,LOC,DA,DA1,
     1DA2,SEQU,(HL(K),K=L,LL)
  100 FORMAT(I1,I2,I1,I2,I1,F3.2,5I2,12F5.3/(20X,12F5.3))
      L=LL+1
      LL=LL+80
    1 CONTINUE
      DO 102 I=1,7
      READ(8,101)AAA
  101 FORMAT(A4)
  102 CONTINUE
  801 DO 29 J=1,NR
      SUM=0.0D0
      DO 26 I=J,NI,NR
   26 SUM=SUM+HL(I)
   29 AVN(J)=SUM/CN
      CALL MEANVR(RBAR,SIGNT,AVN,NR)
      SIGNT=DSQRT(SIGNT)
      PERAV=0.0
      DO 27 I=1,NROW
   27 PERAV=PERAV+(AVN(I)-AVN(I+1))
      PERAV=PERAV/SPRN
      K=0
      DO 4 J=1,NC
      SUM=0.0D0
      DO 5 I=1,NR
      K=K+1
    5 SUM=SUM+HL(K)
    4 AV(J)=SUM/RN
      PARAV=0.0
      DO 28 I=1,NCOL
   28 PARAV=PARAV+(AV(I)-AV(I+1))
      PARAV=PARAV/SPCN
      RSL=(AV(1)-AV(NC))/CNSP
      CSL=(AVN(1)-AVN(NR))/RNSP
      CALL MEANVR(CBAR,SIGT,AV,NC)
      SIGT=DSQRT(SIGT)
      BED=(AV(1)+AV(2)+AV(NC-1)+AV(NC))*0.25
      GAL=0.0D0
      DO 3 I=1,NI
      HL(I)=DLOG(HL(I))
    3 GAL=GAL+HL(I)
      GAL=GAL/TN
      DO 129 J=1,NR
      SUM=0.0D0
      DO 126 I=J,NI,NR
  126 SUM=SUM+HL(I)
  129 AVNL(J)=GAL-SUM/CN
      K=0
      L=0
```

```
      DO 6 J=1,NC
      SUM=0.0D0
      DO 75 I=1,NR
      K=K+1
   75 SUM=SUM+HL(K)
      SUM=GAL-SUM/RN
      DO 6 I=1,NR
      L=L+1
    6 HL(L)=HL(L)+SUM+AVNL(I)
      CALL BSORT(NI,HL,LA,MA)
      J=0
      A=HL(1)
      C=(HL(NI)-A)*(.005D0)
      KK=0
      I=1
   12 IF(HL(I)-A)9,9,90
    9 I=I+1
      GO TO 12
   90 BP=DFLOAT(I-1)/TN
      IF(BP-0.1D0)11,14,14
   14 IF(BP-0.9D0)13,13,15
   13 J=J+1
      IF(J-131)777,778,778
  778 WRITE(3,779)J
  779 FORMAT(' ARRAY SIZE EXCEEDED  J=',I4)
      GO TO 999
  777 X(J)=A
      Y(J)=BP
      YP(J)=CDFN((BP-0.5D0)/DSQRT(BP-BP*BP))
   11 KK=KK+1
      A=HL(1)+(KK*C)
      GO TO 12
   15 SUMX=0.0D0
      SUMY=0.0D0
      SUMXY=0.0D0
      SUMX2=0.0D0
      DO 16 I=1,J
      SUMX=SUMX+X(I)
      SUMY=SUMY+YP(I)
      SUMXY=SUMXY+X(I)*YP(I)
   16 SUMX2=SUMX2+X(I)*X(I)
      FJ=FLOAT(J)
      CONX=SUMX/FJ
      CONY=SUMY/FJ
      B=(SUMXY-SUMX*CONY)/(SUMX2-SUMX*CONX)
      A=CONY-B*CONX
      R=0.0D0
      IF(DABS(B)-0.34E-4)70,70,71
   70 RR=0.0
      RRIN=0.0
```

```
      RAT=0.0
      GO TO 73
   71 DO 17 I=1,J
      YPH(I)=A+B*X(I)
      IF(YPH(I))34,36,35
   34 YH(I)=Y(I)
      GO TO 17
   35 IF(YPH(I)-1.0)36,36,34
   36 Z=CDFNI(YPH(I))
      Z2=Z*Z
      C=0.5D0*DSQRT(Z2/(Z2+1.0))
      IF(Z-0.0D0)18,19,19
   18 YH(I)=0.5D0-C
      GO TO 20
   19 YH(I)=0.5D0+C
   20 R=DMAX1(R,DABS(Y(I)-YH(I)))
   17 CONTINUE
      RR=0.34/B
      RRIN=RR*CBAR
      RAT=SIGT/SIGNT
      RAT=RAT*RAT
      IF(MOD(NOC,2))999,103,104
  104 II=(NOC+1)/2
      ABD(1,II)=RRIN
      GO TO 73
  103 II=NOC/2
      ABD(2,II)=RRIN
      ABD(3,II)=ABD(2,II)-ABD(1,II)
   73 CONTINUE
C  72 WRITE (3,201)NC,PERAV,CSL,CBAR,SIGNT
C 201 FORMAT(1H0,30X,3HNO.,6X,14HSLOPE (PER CT),6X,4HMEAN,6X,
C    15HSIGMA,/,40X,4HINTG,6X,4HENDS,//,16X,7HCOLUMNS,7X,I4,
C    22P2F10.2,0PF10.2,F11.5)
C     WRITE (3,202)NR,PARAV,RSL,RBAR,SIGT
C 202 FORMAT(1H0,15X,4HROWS,10X,I4,2P2F10.2,0PF10.2,F11.5,/)
C     WRITE (3,205)RAT
C 205 FORMAT(1H0,15X,36H(ROW SIGMA / COLUMN SIGMA) SQUARED =,
C    1F12.7)
C     WRITE (3,206)BED,RR,RRIN
C 206 FORMAT(1H0,15X,'SEED BED MEAN =',F7.2,12X,'RANDOM',
C    1' ROUGHNESS (PCT) =',F10.5,5X,'(IN.) =',F10.5)
C     WRITE (3,208)A,B
C 208 FORMAT(1H0,15X,'EST NED =',F10.5,' +',F10.5,' (LN(E)',
C    1' HEIGHT)')
C     WRITE (3,209)R
C 209 FORMAT(1H0,15X,'MAX ABS FRACTION DIFF (OBS - EST) =',
C    1F10.5,/)
C     IF(NEST-0)24,2,24
C   2 GO TO 871
C  24 WRITE (3,23)(I,X(I),Y(I),YP(I),YPH(I),YH(I),I=1,J)
```

```
C   23 FORMAT(1H0,22X,5HCLASS,10X,3HLOG,7X,14HFRACTION UNDER,
C     16X,3HNED,10X,7HEST NED,6X,12HEST FRACTION,//,(23X,I3,
C     23X,5F15.5))
  871 IF(NOC-NODS)30,600,999
  600 WRITE(3,10)
   10 FORMAT('1')
      WRITE(3,21)
   21 FORMAT('0-------------------------------------------------',
     1'-----------------')
      WRITE(3,50)
   50 FORMAT(' ',21X,'ROUGHNESS COEFFICIENTS IN INCHES')
      WRITE(3,60)
   60 FORMAT('+',21X,'________________________________')
      WRITE(3,77)
   77 FORMAT(' TREAT-',10X,'BEFORE TILLAGE   AFTER TILLAGE',
     1'   DIFFERENCE')
      WRITE(3,80)
   80 FORMAT(' MENT    BLOCK         (RRB)              (RRA)',
     1'           (RRD)')
      WRITE(3,95)
   95 FORMAT(' ','------------------------------------------',
     1'--------------------')
      DO 91 I=1,15
      DO 91 J=1,3
      ABD(J,I)=ABD(J,I+15)
   91 CONTINUE
      DO 92 I=16,30
      DO 92 J=1,3
      ABD(J,I)=ABD(J,I-15)
   92 CONTINUE
      ABD(1,20)=10000.0
      ABD(2,20)=10000.0
      ABD(3,20)=10000.0
      WRITE(2,765)(I,ID(I),(ABD(J,I),J=1,3),I=1,30)
  765 FORMAT(I2,I3,3F15.6,'                   ALLMARAS')
      WRITE(3,109) (ID(I),(ABD(J,I),J=1,3),I=1,30)
  109 FORMAT('  RT',I8,F15.3,F16.3,F15.3/5(I12,F15.3,F16.3,
     1F15.3/)/'  PU',I8,F15.3,F16.3,F15.3,/,5(I12,F15.3,F16.3
     2,F15.3/)/'  P ',I8,F15.3,F16.3,F15.3/5(I12,F15.3,F16.3,
     3F15.3/)/'  PODH',I6,F15.3,F16.3,F15.3/5(I12,10X,F5.3,
     411X,F5.3,10X,F5.3/)/'  C ',I8,F15.3,F16.3,F15.3/5(I12,
     5F15.3,F16.3,F15.3/))
      WRITE(3,95)
  999 STOP
      END
C
      SUBROUTINE MEANVR(AVE,VAR,AA,N)
C
      DIMENSION AA(80)
      DOUBLE PRECISION VAR,AA,SUM,SSQ
```

```
      SUM=0.0D0
      SSQ=0.0D0
      DO 1 I=1,N
      SUM=SUM+AA(I)
    1 SSQ=SSQ+AA(I)*AA(I)
      DN=FLOAT(N)
      AVE=SUM/DN
      VAR=(SSQ-SUM*SUM/DN)/(DN-1.0)
      RETURN
      END
C
      FUNCTION  CDFN(Z)
C
      DOUBLE PRECISION Z,A,A1,A2,A3,A4,A5,A6,B,C,D,E,F,PHI
      IF(Z)1,2,2
    1 A = -Z
      GO TO 21
    2 A = Z
   21 A = A/1.414213562
      A1 = .0705230784
      A2 = .0422820123
      A3 = .0092705272
      A4 = .0001520143
      A5 = .0002765672
      A6 = .0000430638
      B = A*A
      C = B*A
      D = C*A
      E = D*A
      F = E*A
      PHI = 1.0D0-1.0D0/(1.0D0+A1*A+A2*B+A3*C+A4*D+A5*E+A6*F)
     1**16
      IF(Z)3,4,4
    3 CDFN = (1.0D0-PHI)/2.0D0
      GO TO 5
    4 CDFN = (1.0D0+PHI)/2.0D0
    5 CONTINUE
      RETURN
      END
C
      FUNCTION  CDFNI(Z)
C
      DOUBLE PRECISION Z,Q,A0,A1,A2,B1,B2,B3,Z1,E1,E2,E3,FZ
      Q = .5
      A0 = 2.515517
      A1 = .802853
      A2 = .010328
      B1 = 1.432788
      B2 = .189269
      B3 = .001308
```

```
      IF (Z) 2,2,1
    1 IF (Z-1.0D0) 5,2,2
    2 WRITE (3,3)Z
    3 FORMAT (10X,21HARGUMENT TO CDFNI IS , 1PE20.10)
    4 GO TO 38
    5 IF (Z-Q) 12,12,10
   10 Z1 = 1.0D0 - Z
      GO TO 15
   12 Z1 = Z
   15 E1=DSQRT(DLOG(1.0D0/(Z1**2)))
      E2 = E1*E1
      E3 = E2*E1
   20 FZ = E1 - (A0+A1*E1+A2*E2)/(1.0D0+B1*E1+B2*E2+B3*E3)
   25 IF (Z-Q) 30,35,35
   30 CDFNI = -FZ
      GO TO 40
   35 CDFNI = FZ
      GO TO 40
   38 CDFNI = -1.0
   40 CONTINUE
      RETURN
      END
```